Land Use Change and Crop Rotation in Rashda Village, Dakhla Oasis, Egypt: Analysis of a Government Well District Based on Satellite Data

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1. Introduction

Dakhla Oasis is located in the heart of the Western Desert in Egypt, 190 km to the west of Kharga Oasis (see **Map**). It contains highly fertile lands and it is rich in water, and it supports a higher population than Kharga Oasis. Dakhla depression extends 155 km in the east-west direction. The area of the oasis that is suitable for agriculture is approximately 155 km long and 60 km wide.

Rashda is one of the villages located in Dakhla Oasis. We have conducted interdisciplinary research, including field surveys, in this village since 2005. We have already published two papers documenting this research. This is the third paper, which aims to provide some analysis based on advanced satellite data that focuses on land use and the crop rotation system. Before starting the discussion, it would be useful to summarize our findings on the irrigation and cultivation systems used in Rashda village. These findings are summarized in terms of the following three issues.

The first issue is the unsustainability of water. The availability of water determines the agricultural economic life in an oasis village such as Rashda. Water is also an essential factor for agriculture in the Nile Valley. However, the latter depends on the Nile where the availability of water can be controlled and estimated in the future. In contrast, it is difficult to plan the use and management of water in the mid- to long-term in the oasis region where agriculture is totally dependent on groundwater availability, because the water flow from groundwater is not controllable. Thus, there is a direct relationship between the locations of wells and springs and the expansion of cultivated lands. In fact, the main concern of farmers should be the quantity of water available, rather than the area of the land they possess.

The second issue is the dependency on the political regime. As noted earlier, the unsustainability of water is a peculiar characteristic of the oasis economy. The availability of water determines the agricultural economic life in an oasis village such as Rashda. The survival of the oasis economy depends largely on the current political and economic regime in general. This is because digging wells and obtaining sufficient water requires large sums of capital and technology, which demands the involvement of the state and private enterprises in agricultural irrigation. The use of water in agriculture leads to a decline in the underground water level. Therefore, it is necessary to dig wells at deeper levels to ensure access to water, which also requires a large sum of money. Thus, although the oasis region might appear to be on the periphery, its survival depends largely on the current political and economic regime in general.

The third issue is the rational behavior of farmers. The farmers have developed a cultivation system to adapt to the natural conditions, which is characterized by the scarcity of water resources. This point is related to the local cultivation customs in the village where local farmers cultivate crops based on their experience. For example, water drainage methods have an important effect on the irrigation system because it is necessary to prevent soil salinity from increasing. However, soil salinization has been observed in the oasis and in the irrigated areas of the village, although this does not mean that the farmers are not conscious of this problem. Instead, the farmers must consider the problem of soil salinization in relation to their

Map of Oases in the Western Desert

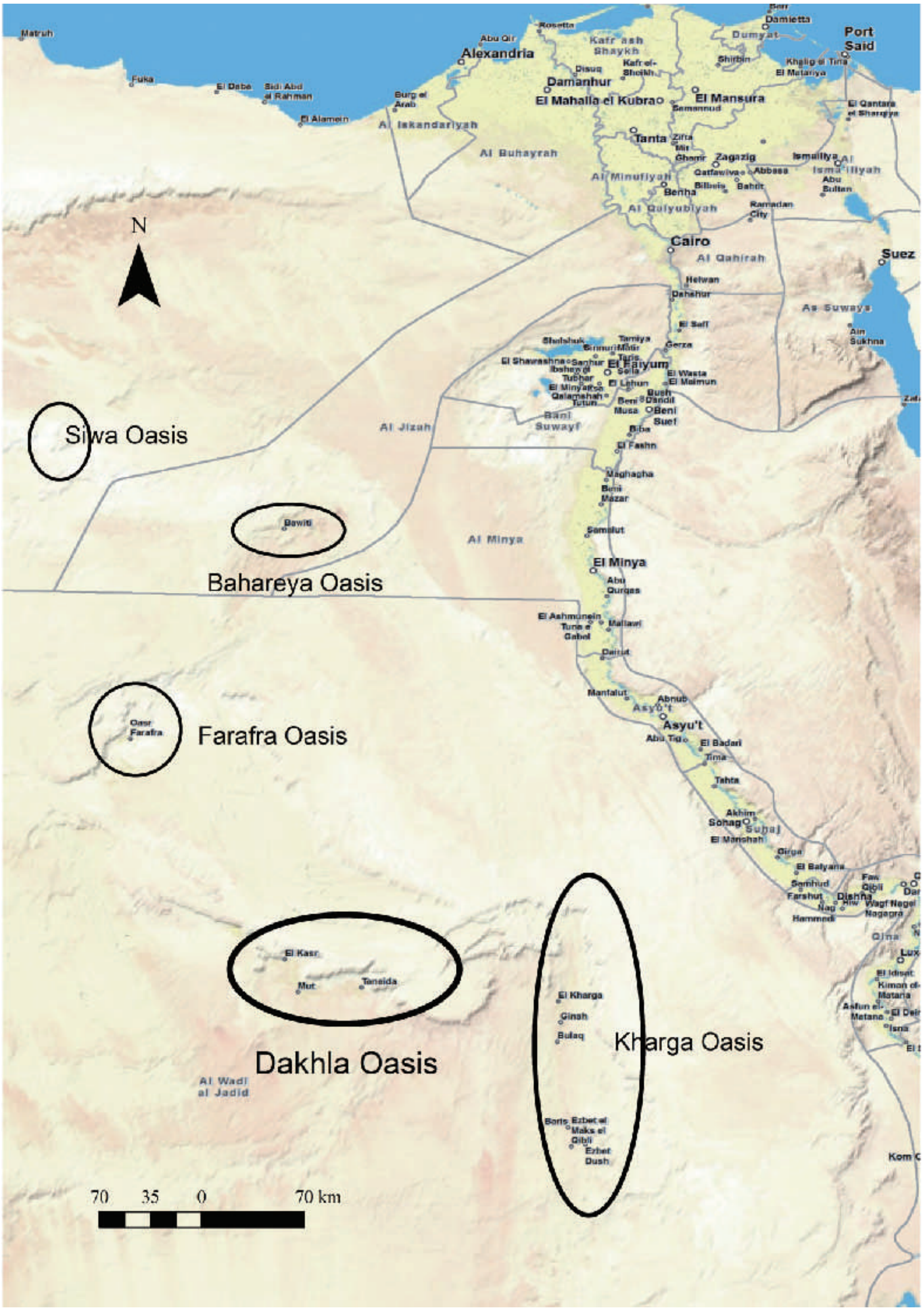
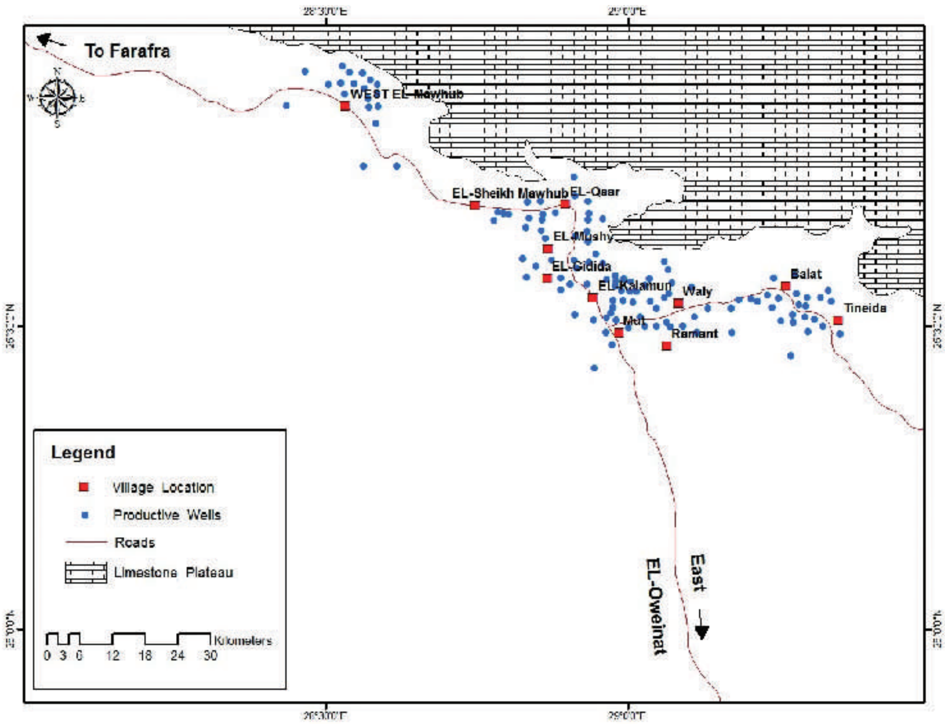


Figure 1: Conceptual map of the residential development in Rashda

Figure 3: Location map of villages and productive wells in Dakhla Oasis



Source: After Gad *et al*., 2011

expenditure. They need to consider the quality of the soil, the availability of capital, and the quantity of water, before they select the most efficient method of irrigation[1].

2. Research site[2]

2.1 Rashda village

2.1.1 Overview of Rashda village

Administratively, Rashda is one of the villages in Markaz Dakhla, Wadi Gedid Governorate. It is the "mother village" of the local village unit of Rashda (*al-wahḍa al-maḥa llīya li-qurā al-rashda*) and it is located 10 km northwest of Mut Town, the administrative center of Dakhla Oasis. Its population is about 5,361.

Although Rashda Village is the second most populous village in Dakhla, it is a new village that was formed in the modern age after the 19th century. The history of the village may be summarized in the following four stages.

(1) Until the mid-19th century, the land that now belongs to Rashda Village was part of Qalamun Village. The peasants of Qalamun moved seasonally to cottages at the foot of a sand hill where they spent the night when conducting agricultural work.

(2) In the second half of the 19th century, a settlement area was created on the sand hill and the peasants migrated there from Qalamun at the same as the migration of agricultural laborers from Balat village (one of the oldest villages in Dakhla Oasis) to the Nazla area. The Nazla area was a marshland at that time.

(3) The inhabitants of the settlement (the "old" area) on the sand hill moved to the western side (the present Qara area) around 1940 and then to the eastern side of the sand hill (the current "new" area) around the 1960s.

(4) From the 1980s, more houses were constructed toward the east in Ezba Mashrukh and in the eastern part of Nazla, and the inhabitants of the "new" area and Ezba Mashrukh migrated to these two areas.

Figure 1 provides a conceptual map showing the development of Rashda from its beginning until the present day.

2.1.2 Hydrogeological conditions

The climate of Dakhla Oasis is characterized as hot and dry, with a high rate of

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1 Parts of this paper are written by the following authors: 1 by Kato, 2 by Iwasaki and Kato, except 2.1.2 by Zaghloul and the first two paragraph of 2.1.3 by Elbeih, 3.1.1 & 3.2.1 by Elbeih, 3.1.2 & 3.2.2 by Kimura and 4 by all authors.

2 This section provides a brief summary of two previous papers on Rashda, which are mentioned above, with the exception of section 2.1.2, which was newly written by Zaghloul, and section 2.2.2, which contains some new information based on field work.

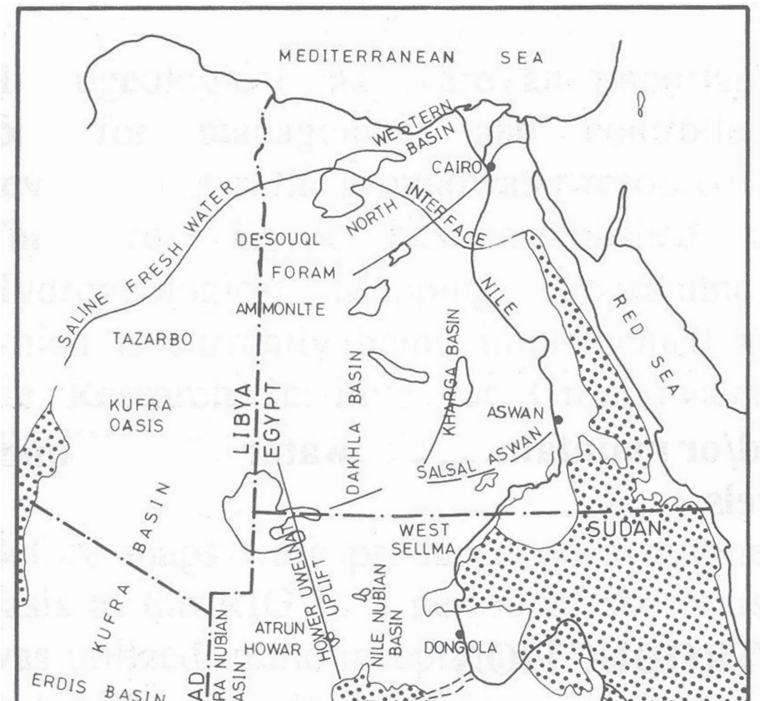
evaporation, a high level of solar radiation (sunshine), and no rainfall.

Since ancient times, the oases have been inhabited by people who have made use of artesian springs in the lowest parts of the depressions found in the Western Desert of Egypt. Irrigated agriculture is facilitated by free-flowing wells, fed by the Nubian Sandstone Aquifer System beneath the major oases (**Figure 2**).

New boreholes were drilled and land was reclaimed between 1982 and 1985, which almost doubled the agricultural area of the Dakhla Oasis. In Dakhla Oasis and the Western Desert of Egypt, groundwater is the main source of water supplies to meet drinking, domestic, and agricultural demands.

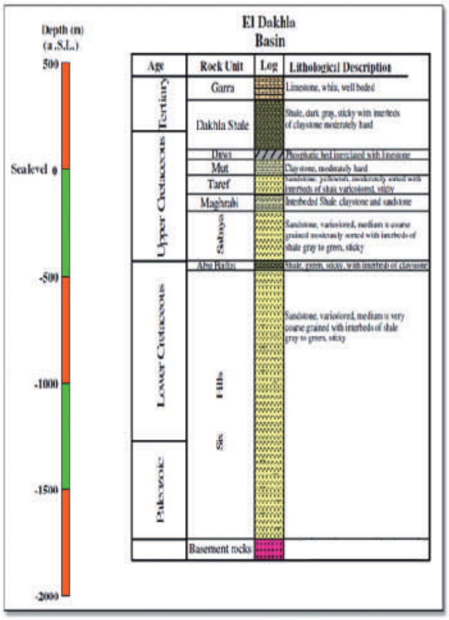
The Nubian Sandstone sequence (Paleozoic to Lower Cretaceous) is the main source of fresh groundwater in the Egyptian Desert (**Figure 3**). It consists of a thick section of coarse, clastic sediments of sandstone and sandy clay, interbedded with shale and clay beds. Its average thickness in the Dakhla Basin is about 1,500 m (**Figure 4**).

Figure 2: Nubian Sandstone Aquifer



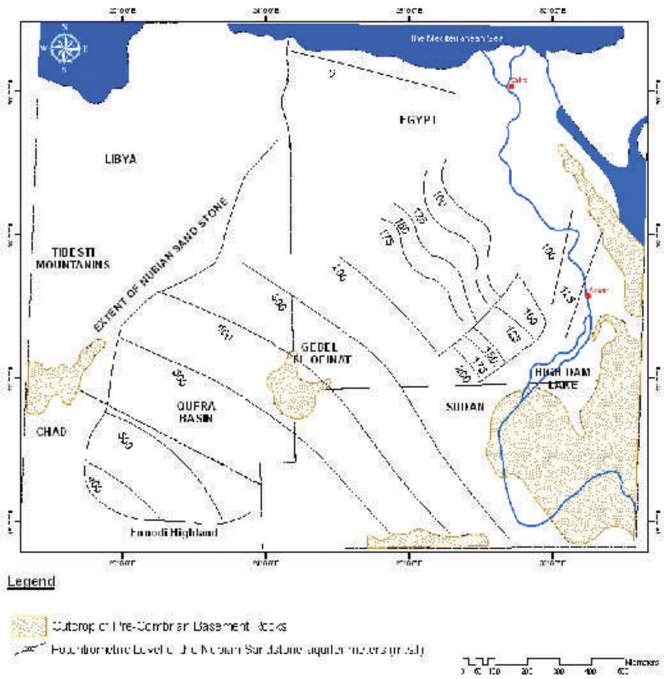
Source: After Hefny, 1991

Figure 4: Generalized section of the Nubian Sandstone Aquifer System in Dakhla Oasis



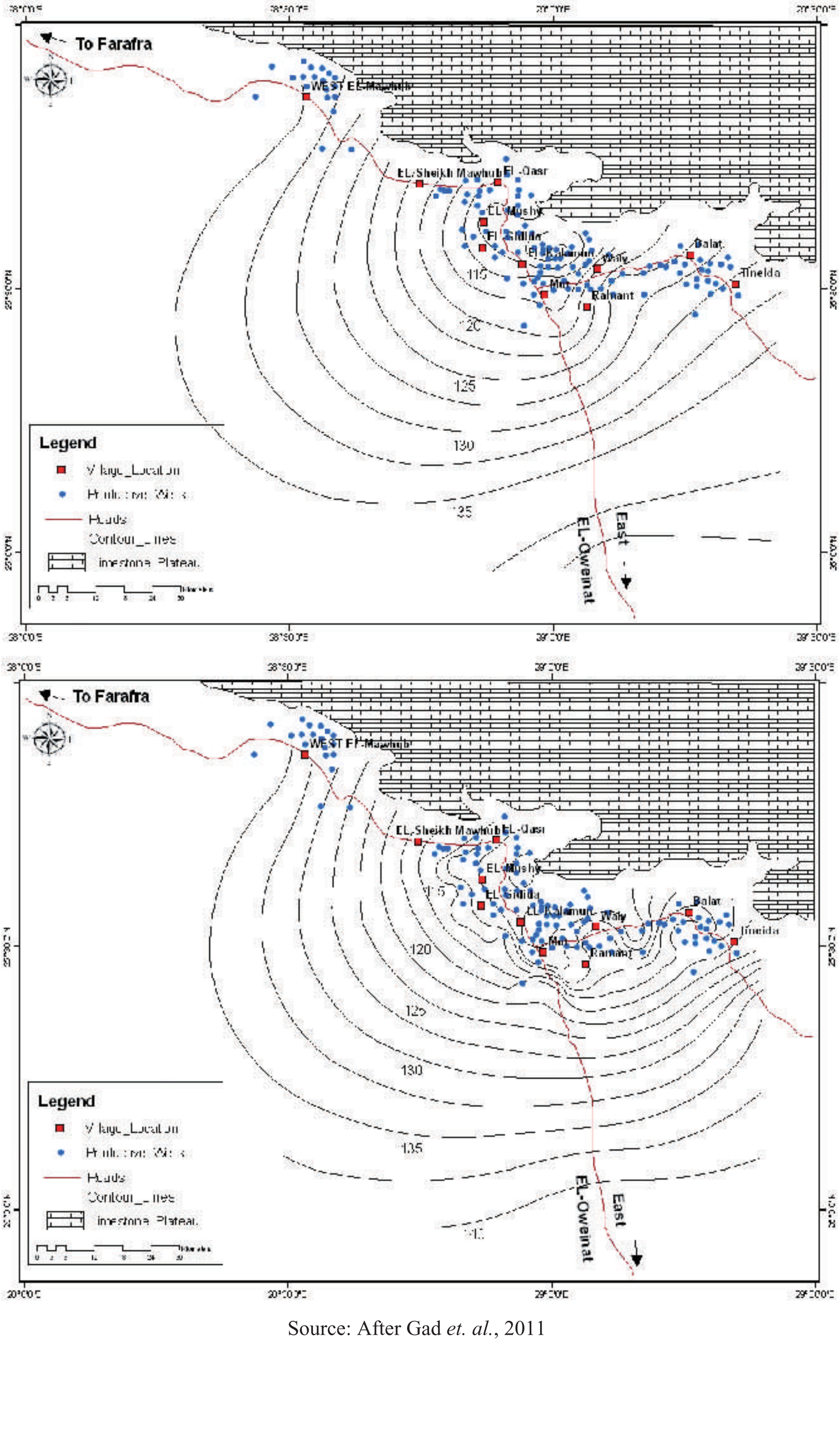
Source: Modified after Heini and Thorweihe, 1993

Figure 5: Piezometric surface contour map of the Nubian Sandstone Aquifer in the Western Desert of Egypt



Source: After Ball,1927 and Sandford, 1935

Figure 6: Piezometric surface contour map of the Nubian Sandstone during the year 2005 (above map) and during the year 2008 (below map)



Source: After Gad *et. al.*, 2011

The aquifer can be classified into three hydrogeological units. The upper unit (upper shallow aquifer) consists of sandstone intercalated with several clay layers, which is capped with a shale bed in the north. The second, or middle, unit consists of shale that forms an aquiclude layer between the upper and lower confined aquifers. The lower unit consists of highly permeable sandstone intercalated with thin clay lenses.

The water was recharged locally during earlier periods with a more humid climate (Pluvial Period) while a small recharge still occurs from exposed intake beds in the humid Tibesti and Ennedi Mountains in Chad. In general, groundwater flows to the north and northeast (**Figure 5**). Based on an isotope analysis, Shata *et al*. (1962) estimated an age of c. 30,000 years for the groundwater at the Dakhla Oasis and they concluded that the groundwater found in the Nubian Sandstone Basin was mainly fossil water.

Recent increases in population and the agricultural expansion has led to an increase in the amount of water discharged from the aquifer (**Table 1**), which currently exceeds the aquifer recharge. Groundwater in the Nubian Sandstone Aquifer has been heavily exploited since 1960. This has led to a decline in the groundwater level (**Figure 6**) and an increase in the salinity

Table 1: Summary of well hydrological data

Well name	Coordinates		Total depth (m.)	Screen position		Water level (m.)	Salinity (ppm.)	Date of well completed	Discharge (m^3/day)
	Lat.	Long.		From	To				
El-Qalamun -1A	25 32 31	28 52 34	744	558	744	119	123	Sep. 57	8800
Rashda - 1	25 34 55	28 54 32	500	298	500	----	----	May 62	11300
Rashda - 1-A	25 34 51	28 54 37	499	302	499	116.5	207	May 73	7560
Rashda - 1-B	25 34 53	28 54 33	299	218	298	109.8	207	Apr. 64	6260
Rashda - 2	25 31 37	28 55 59	500	332	498	116.9	237	Aug. 62	9800
El-Gedida - 1	25 35 55	28 46 59	301	174	301	----	223	Oct. 57	8000

Source: Ezzat, 1975 & Ghoubashi, 2001

The water level ranges from 60–120 m below the ground surface. The salinity is less than 1,000 ppm. Himida (1966) estimated that the deep wells in Dakhla would stop flowing by 1987. According to Gad *et al*. (2011), approximately 13 productive deep wells were discharging about 30,703 m^3 day^{-1} and the total cultivated area was about 1,397 acres. This has led to a continuous decline in the piezometric head of the groundwater (**Table 2**).

Table 2: Changes in the piezometric levels of the observation wells at Dakhla Oasis

Groundwater in the Nubian Sandstone aquifer	Well piezometric head (m.a.m.s.l) & year of observation		Change in head during the observation period
Mut - 3	154.6 (1962)	142.8 (1968)	1.97 (m / year)
Mut Airp ort	130.9 (1965)	123.6 (1997)	0.20 (m / year)
Mawhoub West - 2	140.0 (1964)	138.3 (1968)	0.56 (m / year)
Balat - 8	146.4 (1962)	133.8 (1968)	2.10 (m / year)

Source: Ezzat, 1975 & Gad *et. al.*, 2011

In summary, the population has grown close to groundwater wells over the course of many decades, but people will move to other areas and look for new water supplies when the wells become dry. Diab (1984) stated that the pressure is greatly reduced in the aquifer and most of the springs (*'ain*) have become dry, although few wells are still flowing.

Over the last three decades, the aquifer discharge rate has decreased by 15% and the water level has dropped about 20 m below the initial water level. Water-level drops in deep wells mean that they fail to operate because the water pump is located in the aerated zone (i.e., above the dynamic water level). Thus, the owners of wells (governmental/investment) drilled new wells to replace the ancient wells (replacement wells) in the same area or nearby, as shown in **Table 1**.

Depending on the soil suitability, topographic features, and recent hydrological conditions in the replacement well, a new design was implemented that allowed readjustment of the positions of the screen intervals and the installation level of the submerged water pump.

Thus, the geographic extension of villages was either changed very little or new directions were facilitated for urban expansion. However, some villages were abandoned due to the drying up of water sources (springs or wells) or sand dune encroachments.

2.1.3 Irrigation and cultivation system

Dakhla Oasis mainly depends on groundwater for irrigation and the highest recorded potentiometric surface of shallow wells was about 132 m on the eastern side of the Teneida area, whereas the minimum potentiometric level was 96 m in Rashda Village. This means that groundwater moves towards Rashda village from all directions. The potentiometric level of deep wells was about 130 m in Rashda (NARSS, 2002).

Water resources availability is essential for understanding the economic and social life in Rashda because, as mentioned earlier, the life of villages in oasis regions is dependent on groundwater. The natives refer to the water intake (extraction) wells as *bīr* if the source had to be tapped by a drill, or springs (*'ain*) if the water bubbles up naturally and only needs to be cleared occasionally.

We collected data and information about 70 wells and springs in Rashda Village. The inhabitants recognized the following five types of water source: government well (*bīr ḥukūmī*), local well (*bīr ahlī*), investment well (*bīr istithmārī*), surface spring (*'ain saṭḥī*), and Roman spring (*'ain rūmānī*).

(1) A government well (*bīr ḥukūmī*) is a well that is exploited by the government, which is owned and managed by the Ministry of Irrigation. These wells are generally about 1200 m deep and they are intended to last for 50 years. There were 12 wells of this type in Rashda.
(2) A local well (*bīr ahlī*) is a well that is exploited by local farmers, which has been dug in the traditional manner. These wells are owned and managed collectively by farmers. They are usually less than or equal to 85 m deep. The leader of the well possesses a list of farmers who have water rights. This type of well is intended to last for 20 years. There were 29 wells of this type in Rashda.
(3) An investment well (*bīr istithmārī*) is a well that is exploited by an individual as part of a Public Investment Organization (*al-Hay'a al-Āmma al-Istithmārī*) scheme. A Public Investment Organization is operated by the Ministry of Agriculture and Ministry of Investment. Any individual who wants to start agricultural business is permitted to dig a well after receiving digging permission from this organization. These wells have a maximum depth of 500 m and they are intended to last for 20–30 years. A well is generally owned by a private individual while their irrigated land reverts to private ownership after 10 years rental from the government. There are currently nine wells of this type in Rashda.
(4) A spring (*'ain saṭḥī*) is popularly recognized as bubbling up naturally and it forms when an aquifer intersects with the earth's surface. The depth to the aquifer is generally less than or equal to 120 m. Springs are drilled with the permission of the Land Reclamation Fund. They are collectively owned and managed by local farmers. The irrigated land is rented from the government by farmers, because the land belongs to the government. There were about 34 springs of this type. The first one was constructed in 1998.
(5) Roman springs (*'ain rūmānī*) are popularly recognized as dating back to the Roman era, although most are assumed to be less than 200 years old. They have a depth ranging from 85 to 100 m and they are exploited by local farmers. The leader of a local well has a list of farmers who have water rights and he manages the water schedule. There were eight springs of this type, but all of them have now dried up.

Wells may be referred to in terms of who exploits them, i.e., "government," "local," or "investment." In contrast, the natives distinguish different types of wells based on their depth. Thus, the cost of digging wells is a major issue for village inhabitants. The land is irrigated and cultivated in almost the same manner after digging wells, irrespective of the well type.

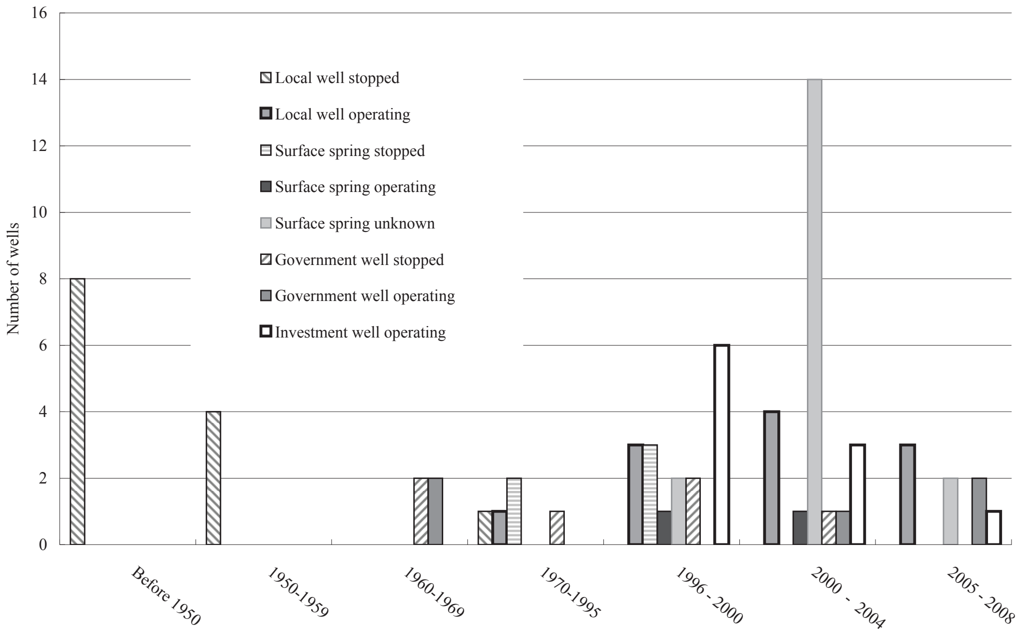
Figures 7 and **8** provide some insights regarding the agricultural circumstances and the history of agriculture in the village, particularly the years when wells and springs were dug.

It can be seen that the development of wells reflected changes in the factors involved in agricultural development. Until the 1950s, local wells were the only source of water in Rashda, so water and agriculture were controlled by the villagers themselves. However, more wells were dug with government support from the 1960s and further changes occurred in the 1990s. Since the latter period, more privately invested wells have been constructed with government support.

It can also be seen that the development of wells and their associated cultivated lands has taken place in the outskirts of the village. **Figure 7** shows that local wells were mainly constructed near residential areas whereas newer wells were constructed in the outskirts.

The last observation is the fragility of water sources in Rashda. **Figure 8** shows that many wells became dry due to drought. It also shows that the development of cultivated lands in Rashda corresponded to the location of wells and springs. These facts explain the two characteristics of agriculture in oasis regions that were highlighted in the introduction, i.e., the unsustainability of water and the effect of the political regime.

Figure 8: Year of construction of wells in Rashda by type of well (2009)



Source: Kato *et al.*, 2010, p. 18

Like other villages in Dakhla Oasis, the most common crops grown in Rashda are wheat and Egyptian clover during the winter, with rice, maize, and dates in the summer. Lands attached to governmental wells do not have palm trees[3]. The main areas cultivated with these crops are shown in **Table 3**.

Table 3: Production of main crops in Rashda (2007)

		Area *(feddan)*	Average production	(Unit)
Winter	Wheat	1129	15804	*ardab*
	Barley	35	280	*ardab*
	Broad beans local	89	979	*ardab*
	Egyptian clover ("strenghtened")	1200	27000	ton
	Alfalfa (*birsim hijazi*)	800		
Summer	Rice	No cultivation by decree on rice cultivation last year		
	Maize	-	-	
	Tomato	5	53	ton
	Potato	5	60	ton

Source: Kato *et al.*, 2010, p. 24

As discussed below, farmers preferred to grow wheat rather than date palms in Well No. 3 Irrigation District because of water scarcity. The cultivation of date palms requires an abundance of water and Well No. 3 Irrigation District is characterized by a lack of water compared with neighboring private artisan wells since the 1970s. Another reason for preferring wheat is to ensure its availability for household consumption.

2.2 Well No. 3 (*bīr* 3) Irrigation District

2.2.1 Overview of Well No. 3 Irrigation District

Well No. 3 (*bīr* 3) Irrigation District was composed of land irrigated by Well No. 3 (*bīr* 3). The area is located to the northwest of Rashda village. The District is divided into three subdistricts (*zimām*), i.e., North (*zimām baḥrī*), South (*zimām qiblī*), and West (*zimām gharbī*) **(Figure 9)**. Well No. 3 Irrigation District had an area of 170–180 *feddan*. The North, South, and West subdistricts had areas of 65, 65–66, and 55 *feddan*, respectively[4].

3 An orchard existed in the North subdistrict that had a claim on irrigation water when the original land was reclaimed for agricultural use. However, part of the orchard was subsequently converted for the cultivation of other crops. When we surveyed the site at Well No. 3, all of the surrounding area contained date palm orchards.

4 The area surrounding this District is also agricultural land. It is a long and narrow lot, which is

Although the area is known as "Well No. 3" Irrigation District, there were actually five wells in this area and they were all government wells.

The first well was drilled in this District in 1959 by an Italian company at a depth of 500 m with an initial discharge volume of 3600 m^3 day^{-1}. The District was originally fallow land on the outskirts of land owned by farmers, which was irrigated using water from a local well. This area was selected for drilling wells because it was fallow and not owned by the farmers. After the first well was dug in 1959 the Egyptian Government reclaimed the District for agricultural use in 1962. The first harvest was in 1963 and fields were first plowed in this District during 1970.

In 1964, the Land Reclamation Office of Wadi Gedid sold a total of 5 *feddan* of land from this District to 34 farmers with 10-year repayment contracts. Under the Land Reclamation scheme, the 5 *feddan* that were sold to each farmer consisted of three plots in each different subdistrict (i.e., the North, South, and West subdistricts). At that time, the distribution of agricultural land ownership was managed by the office to regulate the planting of crops in each district.

The first well, Rashda No. 3, dried up in 1995 and four other wells were drilled by the Department of Irrigation: Well No. 3-5 in 1988, Well No. 3-7 in 1999, Well No. 12 in 2004,[5] and Well No. 3-17 in 2008. The depths of these wells are 831, 530, 1,046, and 739 m, respectively, while the discharge rates at the time of digging were 3,413, 3,413, and 218 m^3 day^{-1} for Well No. 3-5, No. 3-7, and No. 12, respectively[6].

Lands in Well No. 3 Irrigation District are administered by the Rural Development Project, whose local office is in Mut Town. Tenants in the District must pay 40 LE (Egyptian pounds) to the office every season (six months). However, tenants are exempted from paying the rent if the water flow is insufficient and the land cannot be cultivated.

More detailed information is shown in the list of plots **(Table 4)**. The list of plots contains information on the owner names, size of plots, crops cultivated, number of irrigation times, *etc*.

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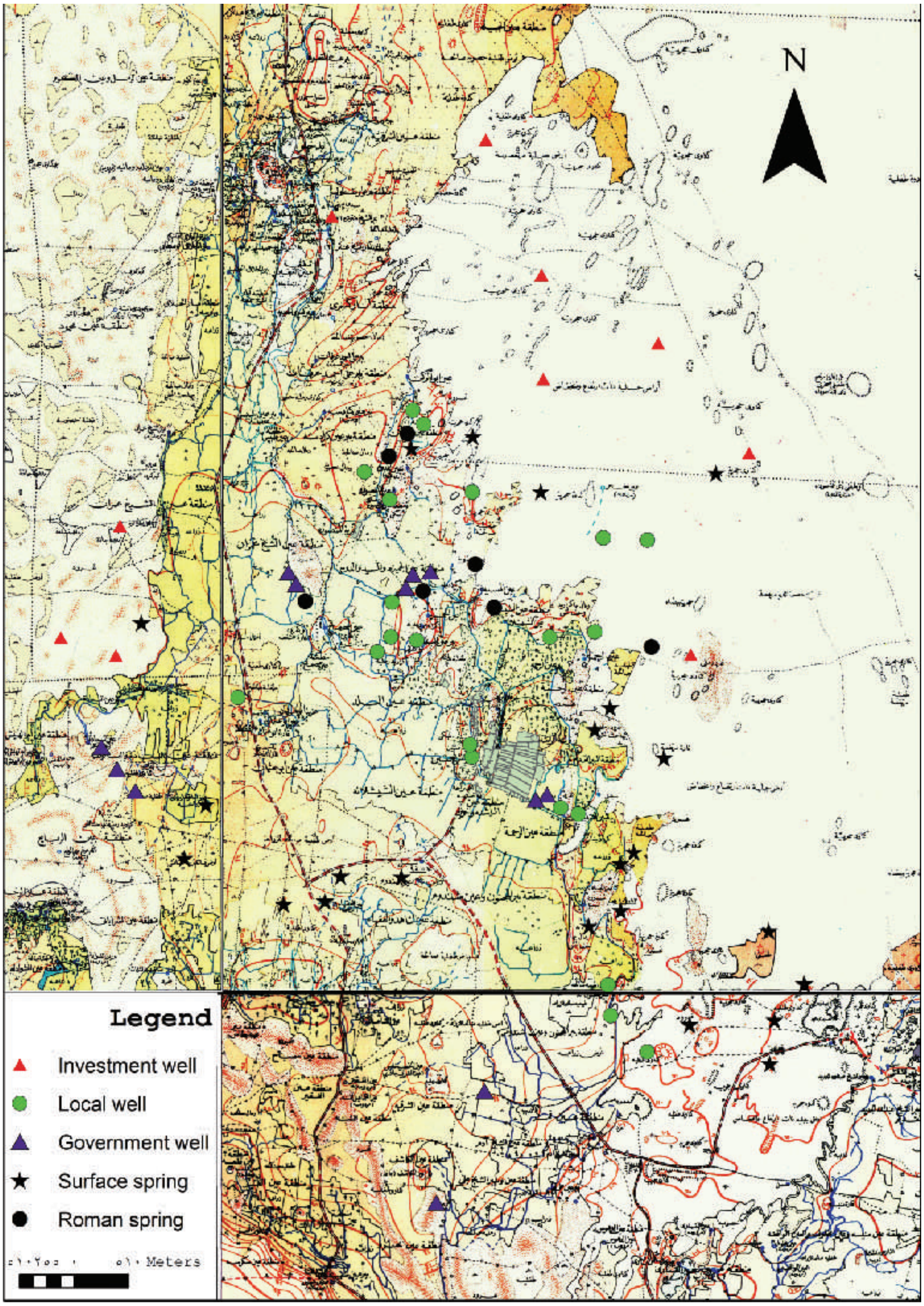
irrigated using local wells. The area on the left of the road leading to the West subdistrict (*zimām gharbī*) is part of the irrigation district. This land is rented to a farmer who lives nearby in this District. However, the lack of water and high salt concentration means that this land has not been cultivated or irrigated since the 1970s. Some plots in the neighboring North subdistrict were also purchased by farmers during the 1980s.

5 Well No. 12 was dug in land owned by a farmer. Thus, this farmer has the right to take water from Well No. 12 to his land, although it is located outside the Well No. 3 Irrigation District. This well was an artesian well. However, a diesel-powered pump with a discharge volume of 150 L min^{-1} was installed at this well in 2006.

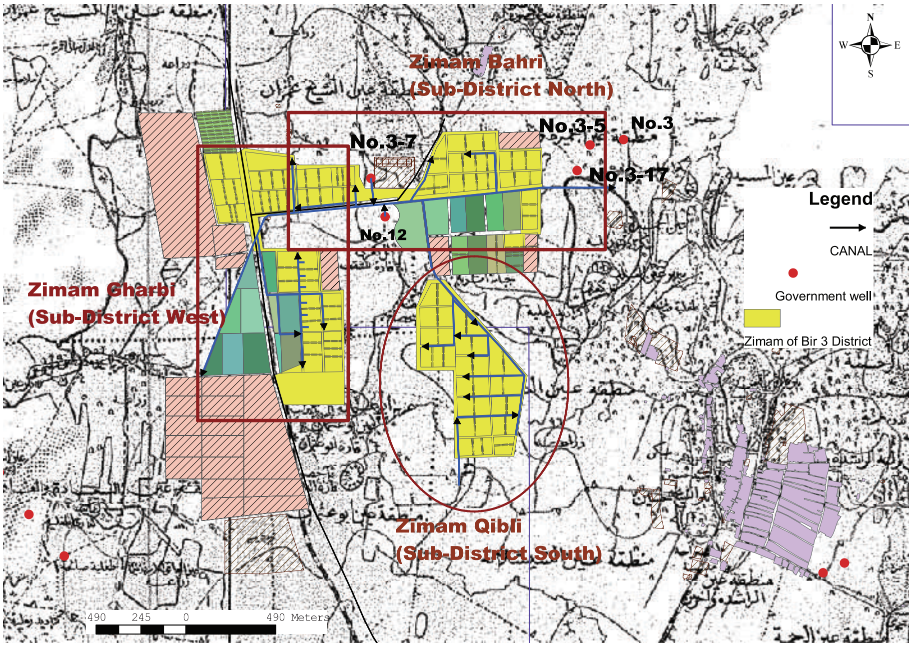
6 Well No. 3-17 was under construction in 2008 when the field survey was conducted. Thus, no data is available on its discharge volume.

Figure 7: Location of wells and springs in Rashda (2007)



Source: Kato *et al*., 2010, p. 15

Figure 9: Location of Well No. 3 Irrigation District



Source: Kato *et al.*, 2010, p. 27

Figure 10: Location of owned plots in Well No. 3 Irrigation District (2009)

Source: Kato *et al.*, 2010, p. 28. Note that 1 amīla equals 30 *qadam*.

Table 4: Size of plots in Well No. 3 Irrigation District (2008)

ID	South		North		West		Total area		Total quantity of water benificied in 3 plots (2007)	
	qirat	*feddan*	*qirat*	*feddan*	*qirat*	*feddan*	*qirat*	*feddan*	*qadam*	*amila*
1	23	1	15	1	14	1	4	5	8	2
2	13	1	3	2	2	1	18	4	15	1
3	2	2	11	1	15	1	4	5	8	2
4	2	2	11	1	8	1	21	4	4	2
5	6	2	4	1	12	1	22	4	5	2
6	13	1	21	1	2	1	12	4	30	1
7	21	1	14	1	16	1	3	5	8	2
8	22	1	16	1	13	1	3	5	8	2
9	12	1	5	1	20	1	13	4	-	2
10	13	1	17	1	15	1	21	4	4	2
11	13	1	19	1	5	1	13	4	-	2
12	2	2	14	1	16	1	8	5	10	2
13	4	2	11	1	16	1	7	5	8	2
14	20	1	18	1	3	1	17	4	2	2
15	7	2	12	1	13	1	8	5	11	2
16	0	2	13	1	15	1	4	5	8	2
17	0	2	23	1	5	1	4	5	3	2
18	2	2	14	1	5	1	21	4	4	2
19	2	2	13	1	5	2	20	5	6	2
20	1	2	11	1	12	1	0	5	3	2
21	1	2	0	1	18	1	19	4	3	2
22	2	2	14	1	2	1	18	4	28	1
23	20	1	16	1	14	1	2	5	7	2
24	18	1	17	1	13	1	0	5	6	2
25	16	1	13	1	18	1	23	4	6	2
26	14	1	13	1	8	1	11	4	29	1
27	14	1	13	1	15	1	18	4	3	2
28	5	2	4	1	5	1	14	4	4	2
29	5	2	2	1	5	1	12	4	-	2
30	6	1	21	1	15	1	18	4	23	1
31	5	1	2	2	14	1	21	4	19	1
32	9	1	16	1	15	1	16	4	2	2
33	8	1	15	1	17	1	16	4	2	2
34	8	1	10	1	19	1	13	4	15	1
Total	21	61	13	53	6	51	16	166	17	70

Source: Kato *et al.*, 2010, p. 30

The extension of cultivated lands around Well No. 3 Irrigation District has changed over the past 40 years. Satellite remote sensing imagery provides an effective tool for monitoring changes in the extension of cultivated lands, as will be explained later.

2.2.2 Irrigation and cultivation system

Water distribution in this District is under the control of the Irrigation Department. An employee of the Irrigation Office and two farmers are appointed as managers of each well. An engineer from the Irrigation Department visits the wells every month to monitor the quantity and quality of water. Wells are also cleaned at the time of the visit.

It takes about one day or night, i.e., from sunrise to sunset or from sunset to sunrise, to irrigate a plot measuring 1 *feddan*. This unit of time is known as an *amīla*. The scarcity and unsustainability of water constrains the agricultural economy in oasis regions, so there is a rotation of the *amīla* periods to ensure that owners take their share of the available water in succession.

This varies depending on the flow of the well and the number of farmers who share it. The size of plots varies between 1 and 2 *feddan* in Well No. 3 Irrigation District so the number of *amīlas* is distributed among the plots as shown in **Table 4**.

In general, each farmer with 5 *feddan* receives 2 *amīla* and 8 *qadam* (1 *amīla* equals 30 *qadam*) during each rotation. The quantity of water distributed to each farmer is decided by the Irrigation Department each season.

There were 34 farmers in the District and each farmer owned three plots in each different subdistrict (**Figure 10**). This method of holding plots in different subdistricts was decided by the Land Reclamation Office when the land was purchased after the first well was drilled.

The winter growing season lasts from October to April. During this season, 22 m^3 of water is irrigated to each 1 *feddan* of agricultural land every 12 days.

The summer growing season lasts from May to September. During this season, water is irrigated to each 1 *feddan* of agricultural land every 16 days. The irrigation interval is longer during the summer growing season because of the scarcity of water for irrigation.

The inadequate availability of water during the summer season means that farmers cultivate only 60% of their land area. In the summer, 30 m^3 of water is required per *feddan* because of the hot and dry climate. However, the actual water distributed is 22 m^3, which is the same as during the winter season. Therefore, many plots remain fallow during the summer season.

This crop rotation role among three different subdistricts is maintained in areas irrigated by government wells. This system has also been in general use in the Nile basin, particularly when rice cultivation was controlled by the government until the 1990s.

The crop types grown and their rotation are decided by the Department of Agriculture (Directorate of Ministry of Agriculture). Meetings are not held to decide the types of crops that will be cultivated because the same cropping pattern is followed every year. This rule is not strictly applied in areas irrigated by private artesian wells. These farmers have greater freedom to decide the types of crops they will grow and when to cultivate them.

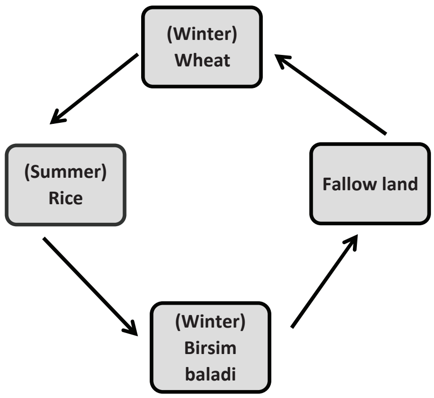
However, the agricultural cooperative has a role in informing and directing farmers in certain circumstances that necessitate the agreement of farmers, such as the prohibition of rice cultivation.

Crop planting was deregulated in the latter half of the 1980s, although cotton planting in the Nile Delta is still regulated. Furthermore, current irrigation laws allow the government to regulate the cultivation of rice paddies depending on the amount of water that is available for irrigation.

Every year, well managers and farmers hold discussions to discuss how much agricultural land can be planted with paddy rice. To determine the area that will be cultivated, they must consider the flow of underground water, pumping tests at the well, and the anticipated irrigation conditions that year.

Rice cultivation requires permanent irrigation and water flows to other crops must be controlled to avoid the overuse of water, which means that crop rotation is necessary. One of the three subdistricts has to cultivate alfalfa (*birsim hijazi)* for three years, while the other two subdistricts follow the crop rotation system shown in **Figure 11**. The crops cultivated in each subdistrict are rotated for three years and six months.

Figure 11: Crop rotation in each subdistrict



Source: Information collected from an informant in December 2011

Table 5 shows the crop rotation system used over the last five years, i.e., 2008–2012. It is important that Egyptian clover (*birsim baladi*) is cultivated in the winter to let the soil rest after rice has been grown in the summer. However, the water scarcity in recent years means that rice was prohibited and land was used either as *bur* (fallow land) or for Egyptian clover cultivation during the rice season[7].

7 Small fields were planted with paddy rice during the summer of 2009, because of the scarcity of water for irrigation. Many fields were left fallow. Farmers were fined if paddy rice was illegally cultivated in these fields.

Table 5: Crop rotation system over the last five years (2008–2012)

	North		South		West	
	Summer	**Winter**	**Summer**	**Winter**	**Summer**	**Winter**
2012	Fallow land	Wheat	Rice		*Birsim hijazi*	
2011	Rice	*Birsim baladi*	Fallow land	Wheat	*Birsim hijazi*	
2010	Fallow land	Wheat	*Birsim hijazi* (instead of rice)	*Birsim baladi*	*Birsim hijazi*	
2009	Fallow land (instead of rice)	*Birsim baladi*	*Birsim hijazi* & maize	*Birsim hijazi*	Fallow land	Wheat
2008	Fallow land	Wheat	*Birsim hijazi* (instead of rice)	*Birsim hijazi*	Rice	*Birsim baladi*

Source: Information collected from an informant in December 2011

As a general rule, the irrigation interval in the District is once every 12 or 16 days. However, continuous irrigation is necessary during the growing period with paddy rice cultivation.

Therefore, the width of a field division was made narrower than the normal width and discharge from the division was reduced to ensure a continuous supply of water to paddy fields.

Thus, the narrower width of field divisions during paddy rice cultivation was 1/12th or 1/16th of the normal width used for ordinary crops.

3. Analysis of land use and crop rotation in Will No. 3 Irrigation District

3.1 Satellite data

The subjects of the research were land use, elevation, and crop rotation.

3.1.1 Analysis of land use and elevation

Three remote sensing satellite images were used to monitor land use changes and elevation.

(1) One Landsat Multispectral Scanner (MSS) image (path 191 and row 42) from November 12, 1972 (http://earthexplorer.usgs.gov).

(2) Two Landsat Thematic Mapper (TM) images (path 177 and row 42) from December 19, 1988 and November 15, 1984(http://earthexplorer.usgs.gov).

(3) Shuttle Radar Topography Mission (SRTM) elevation data from February 2000 (http://www.jpl.nasa.gov/srtm).

The Landsat MSS is a four-channel system that operated between August 1972 and September 1992. Its objective was to conduct repetitive daytime acquisition of high-resolution multispectral data of the Earth's surface on a global basis and to demonstrate that remote sensing from space was a feasible and practical approach for the efficient management of the Earth's resources. Landsat MSS acquired image data in four bands, i.e., reflected green light, reflected red light, and two reflective near-infrared (NIR) bands (NIR1 and NIR2). It had a ground resolution of 79 m and a spectral range of 0.5–1.1 μm, with an image size of 185 × 185 km (Lillesand *et al*., 2004).

The Landsat TM was an MSS radiometer that was carried on board Landsat 4 and 5, which were launched in July 1982 and March 1984, respectively. Landsat gathered data in seven bands. It had a ground resolution in bands 1–5 and 7 of 30 m^2 pixels and a spectral resolution of 0.45–1.35 μm in the visible Near Infrared (VNIR) and shortwave Infrared (SWIR), with an image size of 185 × 185 km.

SRTM obtains elevation data to generate the most complete high-resolution digital topographic database of the earth. SRTM consists of a specially modified radar system, which was transported on board the Space Shuttle Endeavour during an 11-day mission in February 2000. SRTM makes use of a technique called radar interferometry where two radar images are captured from slightly different locations and differences between these two images allows the calculation of the surface elevation in meters.

The images selected were geometrically corrected, calibrated, and removed from any dropouts, before spectral enhancements were performed on the satellite images to facilitate the accurate delineation of the required information.

Automated unsupervised classification of the three Landsat images was applied to identify cultivated areas using the Envi 4.7 software. Ten classes were used during a first iteration of the classification process to separate cultivated lands from the surroundings. The results of this classification were then reclassified into two classes (cultivated and uncultivated) using Arc GIS 9.3 software.

The surface terrain of the area was calculated based on the SRTM data, which was interpolated using the "Topo to Raster" tool in Arc GIS 9.3.

3.1.2 Crop rotation analysis

LANDSAT-5/TM and LANDSAT-7/ETM+ images were used to detect the amount of vegetation and its condition in Well No. 3 Irrigation District. We obtained 108 images during the analysis period between 2001 and 2010.

The Normalized Difference Vegetation Index (NDVI) provides a measure of the amount of vegetation on the land surface (Rouse *et al*., 1974). In general, higher NDVI values indicate greater amounts of vegetation. The NDVI can be estimated from the reflectance of bands 3 and 4 using the following formula:

$$NDVI = \frac{\rho_4 - \rho_3}{\rho_4 + \rho_3}$$

$$\rho_\lambda = \frac{\pi \cdot L_\lambda}{ESUN_\lambda \cdot \cos\theta \cdot d_r}$$

where ρ_4 and ρ_3 are the reflectance for band 4 and 3, λ is the band number, L_λ is the sensor observed radiance for band λ (W m^{-2} ster^{-1} μm^{-1}), $ESUN_\lambda$ is the mean solar exoatmospheric irradiance for band λ (W m^{-2} ster^{-1} μm^{-1}), θ is the solar incident angle normal to the surface, and d_r is the inverse squared relative distance between the Earth and the Sun.

The Normalized Difference Water Index (NDWI) is a satellite-derived index acquired from the NIR and SWIR reflectance, which provides a measure of the amount of water in vegetation canopies (Gao, 1996). The NDWI is calculated using the following formula, which is the same as that used to determine the NDVI:

$$NDWI = \frac{\rho_4 - \rho_5}{\rho_4 + \rho_5}$$

where ρ_5 is the reflectance for band 5.

The North, South, and West subdistricts in Well No. 3 Irrigation District were classified polygonally using the image shown on **Figure 9** and the averaged NDVI and NDWI values were calculated for each subdistrict. The resolution of Bands 3, 4, and 5 was 30 m.

3.2 Results of the analysis

3.2.1 Land use change and elevation

3.2.1.1 Situation in the three subdistricts of Well No. 3 Irrigation District between 1972 and 1988

The aim of this section is to demonstrate that remote-sensing images can be a useful tool for monitoring changes in the extension of cultivated lands over time. We investigated the extension of cultivated lands in the 1970s and 1980s around Well No. 3 Irrigation District as a prelude to a more detailed research study in Rashda Village and Dakhla Oasis.

Figures 12 (a-c) show the results of the unsupervised classification and the extension of cultivated land in Well No. 3 Irrigation District relative to Roman springs in 1972, 1984, and 1988. It can be seen that the northwestern part of the West subdistrict was a fallow land (*būr*) in 1972 and 1984, whereas it was cultivated in 1988. Thus, the West subdistrict was not fully developed until 1988. **Table 6** shows changes in the area of cultivated lands in Well No. 3 Irrigation District of Rashda Village between 1972 and 1988. It can be seen that the area of cultivated land in the South subdistrict and West subdistrict increased by about 12.3% and 12.1%, respectively, between 1972 and 1988. In contrast, the area of cultivated land in the North subdistrict decreased by about 8.8% over the same period.

Table 6: Variation in the area of cultivated land from 1972 to 1988 in the three subdistricts of Well No. 3 Irrigation District

Year	South (Zimam Qibli)		North (Zimam Bahri)		West (Zimam Gharbi)	
	m^2	feddan	m^2	feddan	m^2	feddan
1972	199776.40	49.4	188199.72	46.5	204516.77	50.5
1984	221996.41	54.9	170414.13	42.1	194743.15	48.1
1988	224617.94	55.5	171743.01	42.4	229079.15	56.6

3.2.1.2 Elevation level and geographical features of the three subdistricts

The elevation of the three subdistricts was estimated from SRTM data (**Figure 12**). The elevation of the West subdistrict and South subdistrict was lower than that of the North subdistrict.

3.2.2 Crop rotation

Figure 14 shows the seasonal NDVI variation for each subdistrict between 2001 and 2010. The solid line represents a polynomial equation with six orders. The three polynomial lines meet in the lower right of the figure. The NDVI value reached its maximum (about 0.57) around mid-February and it decreased drastically until the end of May in all subdistricts. This is a typical growth pattern for winter wheat from anthesis to maturity (Moriondo *et al*., 2007).

The NDVI value decreased in order in the South, North, and West subdistricts during the winter season. The maximum NDVI value (about 0.57) was low compared with values of 0.7 to 0.8 found in southern Italy (Moriondo *et al*., 2007). A significant change in the NDVI can be seen among the areas during the summer season. After harvesting, some crop types were planted and cultivated from the beginning of November in the South subdistrict, whereas the land remained fallow in the North and West subdistricts. However, the low amplitude represents some form of cultivation in the West subdistrict.

The winter wheat planting season begins in about November in the North, South, and West subdistricts. **Figure 15** shows that there was a distinct difference in cultivation systems between the summer and winter season. The high irrigation water volume required for cultivation in the hot and dry summer climate (Kato *et al*., 2010) means that fallow or small scale cultivation is more suitable for Rashda Village in the Dakhla Oasis in this season.

Table 7 shows the growing conditions in each subdistrict during the winter season, from January to May. The circle indicates good conditions above the solid line in **Figure 15**, the cross indicates bad conditions below the solid line, while the triangle indicates uncertainty due to a lack of data. The growing conditions were good in all subdistricts during 2001, 2004, and 2009, but bad during 2006 and 2010. There were two good and one bad subdistrict during 2003, 2005, 2007, and 2008. There were 34 farmers in Well No. 3 Irrigation District and each owned land in the North, South, and West subdistricts. Farmers may have been content to maintain production in at least two areas when the irrigation water was limited.

Figure 16 shows the relationship between NDVI and NDWI. NDWI provides a measure of the amount of water in vegetation canopies, which is an indicator of water stress. The NDWI can serve as an index of the irrigation volume if we assume that the amount of water in vegetation canopies is related to the soil water content. Based on this assumption, the following can be concluded from **Figures 15 and 16**:

(1) The NDWI value decreased in order in the South, West, and North subdistricts, when the NDVI was <0.45, even if the NDVI value was the same in **Figure 16**. However, the NDVI decreased in order in the South, North, and West subdistricts in **Figure 15**. The irrigation level was higher in the West subdistrict compared with the North subdistrict, whereas the vegetation amount in the West subdistrict was lower than that in the North subdistrict.

(2) The NDWI decreased in order in the North (≈ West) and South subdistricts when the NDVI was >0.45. In the South subdistrict, steady plant growth was maintained when the irrigation level was lower than that in other subdistricts. The North and West subdistricts required more irrigation water to maintain the same production level as the South subdistrict.

Based on these results, the features of each subdistrict may be represented as follows:

(1) South subdistrict: the relationship between the irrigation level and plant production was favorable.

(2) North subdistrict: plant production was well maintained, although the irrigation level was small compared with the South subdistrict.

(3) West subdistrict: plant production is low regardless of the irrigation level, although this was comparatively large.

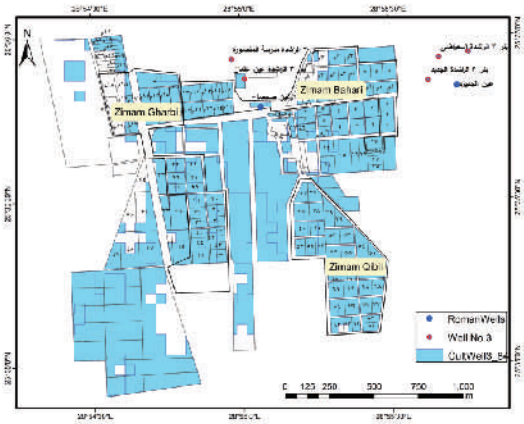
Table 7: Growing conditions in each subdistrict during the winter season (January to May)

	Subdistrict N	Subdistrict S	Subdistrict W
2001	○	○	○
2002	△	△	△
2003	○	○	×
2004	○	○	○
2005	×	○	○
2006	×	×	×
2007	○	○	×
2008	○	×	○
2009	○	○	○
2010	×	×	×

Figure 12: Extension of cultivated land around Well No. 3 Irrigation District between 1972 and 1988

a)1972

b)1984



c)1988

Figure 13: Elevation levels of the three subdistricts

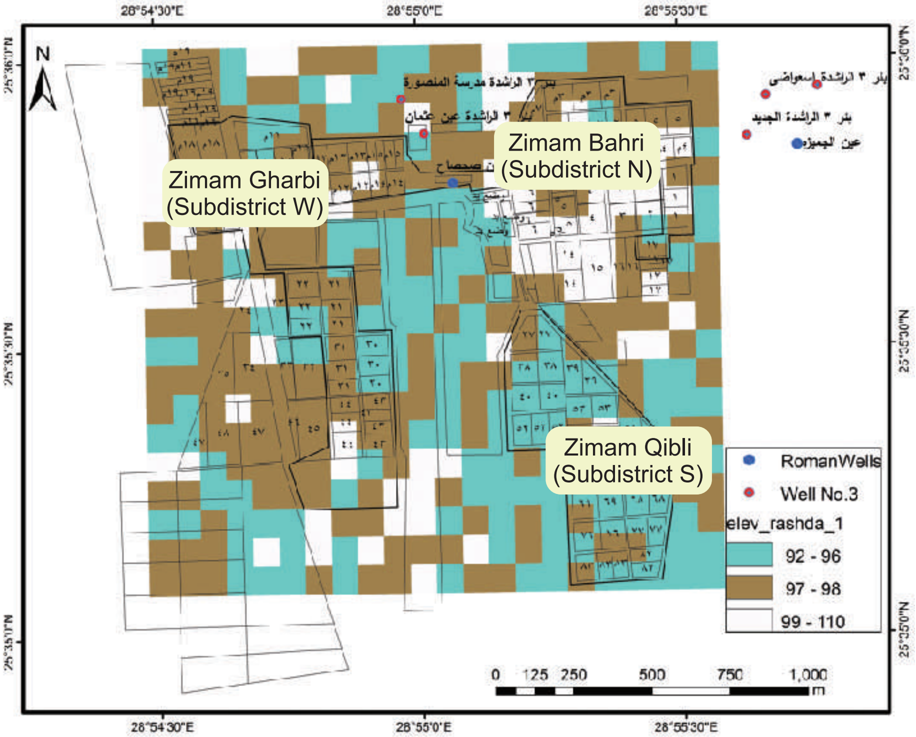


Figure 14: The North, South, and West subdistricts in Well No. 3 Irrigation District

Green : North Red : South Blue : West

Note: This map is cited from Google Maps.

Figure 15: Seasonal variation in the NDVI in each subdistrict between 2001 and 2010

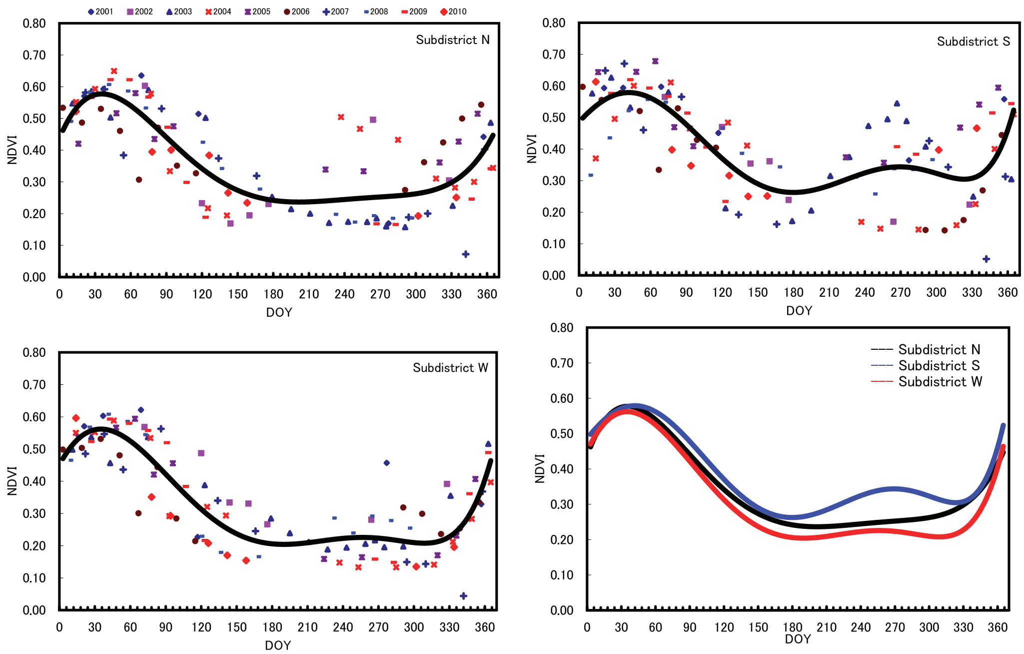
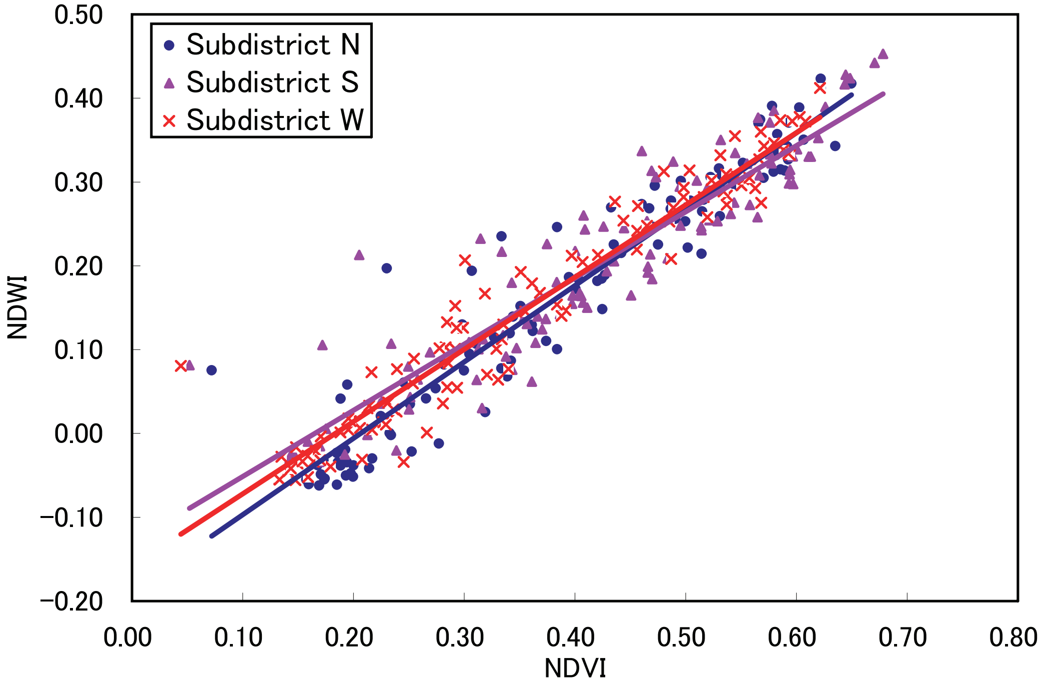


Figure 16: Relationship between NDVI and NDWI



Birsim hijazi (alfalfa)
in Zimam Qibli (Subdistrict South) 2009 Summer

Birsim hijazi in Zimam Qibli (Subdistrict South)

Green onion in Zimam Qibli (Subdistrict South)

Rice field in Well No.3 District 2010 Summer

Seeding in Zimam Qibli (Subdistrict South)
2011 Summer

Well in Well No.3 District

4. Conclusions

To supplement our two previous papers on the economic and social life in Rashda Village, this report aimed to provide additional information based on a new source of information, i.e., satellite data. The subject of this study was the relationship between water resources and land use, particularly land use change and efficiency.

This analysis has just begun and the research will need to be extended qualitatively and quantitatively. However, this study already has some important implications for our future research. We conclude this paper by highlighting these implications and taking into consideration our findings on the irrigation and cultivation systems used in Rashda Village, which we deduced from the research results in our two published papers.

The main findings in the two previous papers were as follows: the unsustainability of water, political regime effects, and the rational behavior of farmers.

Hydrogeological data on underground water demonstrated the relative abundance of water in Rashda, because groundwater moves in all directions toward Rashda Village. This was also demonstrated by the cultivation of rice, which is a crop that requires an abundance of water for its cultivation.

However, the availability of water is limited because the groundwater in Rashda is mainly fossil water. Our field survey site was land in Well No. 3 Irrigation District, where four of the five wells used for irrigation had dried up by 2008. The unsustainability of water in Rashda was explained analytically in section 3.2.1 where the extension of cultivated land was connected to the possible water distribution.

The groundwater level is becoming increasingly lower as the fossil water is consumed. This also leads to a dependency on the political regime to sustain the water required for cultivation, because it is expensive to dig the deep wells that are required to extract underground water from low levels. In fact, all of the five wells in Well No. 3 Irrigation District were government wells, because Well No. 3 Irrigation District was located in the nonfertile area of Rashda.

The cost of digging deep wells was borne by the government and the land in Well No. 3 Irrigation District was divided into three subdistricts, which were distributed among farmers based on the principle of equality. However, the water distribution and cultivation of land irrigated by the well is managed by farmers after the well is completed and the land is distributed by the government.

Farmers manage irrigation and cultivation by adapting to the natural conditions of water and land. Thus, they must consider the quantity of water available, the soil type and capacity, and the availability of capital and labor, before selecting the most efficient method of cultivation, while also promoting local farming customs. This explains the different productivity of the three subdistricts in Well No. 3 Irrigation District, which was discussed in terms of crop rotation in section 3.2.2.

The land use change analysis provided in section 3.2.1 showed that the extension of cultivated land was already completed by the 1980s in the North and South subdistricts, after which it spread in the West direction. Because the altitude in the West subdistrict is lower than the wells, irrigation water could be distributed adequately if the condition of the irrigation channel was well maintained.

However, the relationship between the irrigation level and plant production was not favorable in the West compared with other subdistricts. This may indicate that the distance from the well had a strong effect on plant production in Rashda Village. The cultivated area in the West subdistrict has been increasing since the 1970s. The maintenance of irrigation channels to reduce water loss is important for continuous plant production.

It is possible that the different productivity of the subdistricts, as shown in the crop rotation analysis, was caused by a complex range of many factors, including the land altitude and the distance from the well, as well as other factors such as soil salinization, water quality, and social relationships in the village and families. However, these subjects will be addressed in future research. The variation in the water level and quality will also be linked with the pattern of the spread of the cultivated land in future research.

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