Comparing water capacity and water usage in the Gorom-Lampsar river system, Senegal

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Abstract
This study was performed in the Senegal River delta, north-east of the city of Saint-Louis in Senegal. In this area there is a network of channels originating from the Senegal River. These channels provide water for the irrigation of the cultivated land in the region. The aim of this study was to investigate the water capacity, the existing irrigation capacity and the water usage in the part of the delta which is called the Gorom-Lampsar river axis. This allows for a comparison of the results from the different parts of the investigation and a discussion on potential expansion of the cultivated land.

The water capacity was investigated by assessing the characteristics of the head regulators in the Gorom-Lampsar system and using mathematical equations to calculate the discharge. Discharge measurements using ADCP were also made to verify the calculations and make comparisons. The existing irrigation capacity was investigated by an assessment of the capacity of the pumping stations in the Gorom-Lampsar system. The water usage in the system was estimated by investigating the amounts of water used in parts of the irrigated land during the last irrigation campaign.

The results of the study show that the water capacity in the Gorom-Lampsar river axis is greater than both the water usage and the existing irrigation capacity. This implies that an expansion of the irrigated land in the system may be possible. However, parts of the investigation were based on uncertain data and therefore further investigations need to be done in order to confirm the results of this study. Some simple improvements of the water management are suggested to facilitate for further investigations of the water capacity.

Keywords: Water capacity, water usage, discharge, irrigation, Senegal River
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1. Introduction

Surface water has always been of great importance for humans and good surface water management is essential for a well-functioning society. Large amounts of the world’s surface water are used for irrigation to support food production. In some dry regions of the world crops could never be grown without the construction of irrigation systems (U.S. Geological Survey, 2013).

The Senegal River in the northern part of Senegal is located in Sub-Saharan Africa in the arid Sahelian zone. The development of an irrigation system in the area has improved the agricultural conditions significantly and cultivation is now possible year round in fairly large areas (Dia, 2013). In spite of this, Senegal still imports large amounts of staple products (Landguiden, 2012). There is a desire to reduce importation by improving the farming conditions. This would enhance the economy of the country and provide work for the people of Senegal. A necessary condition for increased food production in the country is the availability of water for irrigation. When investigating the possibilities to increase the extent of agriculture and irrigation in the Senegal River delta, it is necessary to investigate and compare the water usage and the water availability.

This study will focus on the part of the delta located in north-western Senegal, close to Saint-Louis, where information about the water usage and the discharge in different parts of the river system is limited (Dia, 2013). The area, which is called the Gorom-Lampsar axis, is highly regulated. It is dependent on the water capacity of the two main inlets where water is lead from the Senegal River into the system of smaller channels. In general all new information about the discharge and water usage is of great value to managing this region. This study will focus on estimating the maximum discharge in the inlets, referred to as the capacity, and the water usage at two management levels.

1.1 Aim
The aim of the study was to evaluate the water capacity in the Gorom-Lampsar river system. Furthermore, the existing irrigation capacity is evaluated with regards to the pumps along the river system. Lastly the actual water usage in part of the study area will be investigated based on documentation from the latest irrigation campaign. The study will contribute to a greater
understanding of the complex river system and will enable a comparison between the water availability and the water usage.

1.2 Questions of issue

• What is the relation between the water capacity, the existing irrigation capacity and the water usage in the Gorom-Lampsar system?
• Is an expansion of the irrigated area possible?
• Will the water demand be satisfied in the next coming irrigation campaigns?
• How can the management of the channels and water resources be improved?
2. Background

2.1 Study area
The Senegal River basin (Figure 1) has a drainage area of approximately 375 000 km² and is located in Senegal, Guinea, Mali and Mauretania (Andersen et al., 2001). The agricultural activities in the river delta are highly dependent on the river water, either as natural flooding or as pump-based irrigation (Rasmussen et al., 1999). The area is part of the Sahelian and subtropical climate zones of West Africa (Venema et al., 1997). The mean temperature is 25 °C (Bouisse et al., 2010) and the average annual rainfall is 200-300 mm. This rain falls during three or four months from June to September (SAED, 1997). In the dry period of the year the area is often subject to drought (Venema et al., 1997).

![Figure 1. The Senegal River basin (UNESCO, 2012).](image)

The area concerned in this project is the part of the delta surrounding the Gorom channel and the Lampsar channel (Figure 2). The Gorom and the Lampsar are two of the most important channels in the river delta. The Gorom channel is divided into two parts: the Upstream Gorom (25 km long) and the Downstream Gorom (30 km long). These are receiving their water from the Senegal River via two head regulators (main regulators). The area is very flat and therefore highly dependent on the regulation of these two structures. The regulator that feeds the Upstream Gorom is located in Ronkh and the regulator that feeds the Downstream Gorom is called the G-gate. The Upstream Gorom and the Downstream Gorom meet in Boundoum to form the Lampsar channel. From Boundoum the Lampsar flows more than 70 km reaching
Bango, from where the drinking water of Saint-Louis is taken (Bouisse et al., 2010). The Kassack, the Diawel and the newly constructed Krankaye are other important channels in the area. The channels in the delta, which are also called “axes”, are used for irrigation of the agricultural land surrounding them. The irrigated land areas in this project are referred to as “the perimeters”. The irrigation water is taken from the axes to the perimeters via pumping stations. No water is being pumped directly from Krankaye for irrigation but this axis was constructed only to give enough discharge into the Lampsar.

![Figure 2. The Gorom-Lampsar river axis.](image)

2.2 Water Management

*OMVS*

Senegal, Mali, Mauretania and Guinea, which are the four countries connected to the Senegal River, are collaborating in a development authority called the Organisation pour la Mise en Valeur du Fleuve Sénégal (OMVS). OMVS is managing the river development and its main objectives are to ensure an environmentally and economically feasible, and in the long term, durable usage of the river resource. The authority’s efforts mainly concern hydroelectricity,
seafaring and transport, drinking water development and purification, and rural development (OMVS, 2013). OMVS has managed realized the construction of two big dams in the river. The Manantali dam in Mali ensures irrigation of a large agricultural region and is also producing hydropower. The Diama dam in Senegal was constructed to prevent saltwater intrusion from the sea into the river delta. The dam also functions as a water storage facility for irrigation and it has a gate for navigation purposes (Venema et al., 1997).

**SAED**

La Société Nationale d’Aménagements et d’Exploitation des Terres du Delta du Fleuve Sénégal et des Vallées du Fleuve Sénégal et de la Falémé (SAED) is a Senegalese government agency responsible for irrigation development in northern Senegal. SAED was formed in 1965 and until 1980 it was a public organization. Since 1980, the Senegalese government and SAED are working together on establishing contracts with agreements regarding the river management. SAED is responsible for the water management of approximately one third of the Senegal rural land and its mission is to develop the irrigation of the left bank of the Senegal River (the Senegalese side of the river). The major objectives are to improve and secure the base production of food, to increase the production and productivity and to coordinate the operators involved in the agricultural activities in the area. Some of the activities are construction and maintenance of the hydro-agricultural infrastructure, water and environmental management, rural land development and support for organizations and farmers.

The water management is practiced on three levels: the Senegal River, the hydraulic axes and the perimeters. The hydraulic axes are the channels linking the perimeters to the Senegal River. They were originally natural but have been reshaped for the purpose of water transportation. SAED is managing the Senegal River and the axes while the perimeters are managed by the farmers. However SAED is supporting and controlling the farmers’ water usage. SAED is also taking part in the management of the perimeters which were constructed before 1990 and which have not been rehabilitated. The work is financed by four funds to which both the government and the farmers are contributing.

In northern Senegal rice is the main crop but vegetables such as onions and tomatoes are also of great importance. The cultivation of the perimeters is divided into three campaigns: the dry and cold campaign (October-February), the dry and hot campaign (February-June) and the
wet campaign (June-October). Vegetables are grown during the dry and cold campaign and rice is grown during the remaining two campaigns. The government has a goal that by 2018 Senegal will have established a self-supporting rice production. Even though the extent of cultivated land has increased (thanks to improved and expanded irrigation) by more than 100% since year 2000, one third of the rice demand in Senegal is produced in the country and the rest is imported. 80% of the rice produced in Senegal comes from the area managed by SAED (Dia, 2013).

**MCC and MCA**

In September 2009 the Millennium Challenge Corporation (MCC) and Senegal signed a five year agreement aiming for reduced poverty and economic growth in the country of Senegal. The goals established will be reached through two larger projects funded by the Millennium Challenge Account (MCA). One of the projects deals with the extension and improvement of the irrigation system in the Senegal River Delta (MCC, n.d.). Some of the work that will be done include the expansion of various structures, clearing of vegetation and eroded material of the channels and enlargement of the embankments. The purpose is to increase the water flows in the delta and improve the water quality. The MCA project also covers social and environmental issues related to the water usage in the area (Niane, 2013).

The MCC project is still at the preparation stage and SAED is therefore continuously working with maintenance of the channels to keep the water capacity at a proper level (Niane, 2013). The deadline of the MCC project is in September 2015. Until then the capacity of the Gorom-Lampsar axis is based on the current conditions.
3. Theory

In this chapter, the theory for the flow calculations and some of the methods used in this project are described.

3.1 Calculation of flow through a sluice gate
Discharge measurements are generally hard to obtain; as such there are several techniques to do indirect measurements or to calculate discharge based on mathematical and empirical formulas. The discharge in an open channel can be calculated based on stage data if there is an unequivocal relationship between stage and discharge, and if a good gauging site is available. The location must have a stable riverbed profile and be well regulated, and the geometry should not change with variations in discharge. Moreover, the flow should be slow and uniform. If these conditions are met it is possible to find a suitable stage – discharge relationship for the site (Shaw, 1983).

Sluice gates are common structures in open channels to regulate and calculate flow for water management purposes. Although the flow through sluice gates is complex under authentic conditions, it is commonly divided into two regimes: free flow conditions and submerged flow conditions (Figure 3).
In the first case the flow is independent of the tail water depth and in the second case there is a dependency of both upstream and downstream water depth (Nasehi, Oskuyi and Salmasi, 2006). There are several ways of determining if the flow conditions are free or submerged. Swamee (1992) used the relationship between the upstream and downstream water level to determine the flow regime. Conditions must be met according to Equation 1 or Equation 2 and consequently the flow regime can be decided.

\[ y_1 \geq 0.81 \cdot y_3 \cdot \left( \frac{y_3}{b} \right)^{0.72} \] \hspace{1cm} Equation 1 (Free flow)

\[ y_3 < y_1 < 0.81 \cdot y_3 \cdot \left( \frac{y_3}{b} \right)^{0.72} \] \hspace{1cm} Equation 2 (Submerged flow)

In this study no equation was used to decide free or submerged flow but submerged flow was assumed from examining the river at the locations of interest.
The discharge of water through a sluice gate is driven by the stage difference between upstream and downstream the gate. In general, the mechanical energy level of flowing surface water can be determined with the Bernoulli equation (Equation 3)

\[
\frac{v^2}{2g} + z + \frac{p}{\rho g} = \text{constant}
\]

Equation 3

where \(v\) is the water velocity, \(g\) the acceleration due to gravity, \(z\) the elevation, \(\rho\) the water density and \(p\) the water pressure.

For a sluice gate the Bernoulli equation can be written as in Equation 4.

\[
\frac{v_1^2}{2g} + z_1 + \frac{p_1}{\rho g} = \frac{v_2^2}{2g} + z_2 + \frac{p_2}{\rho g}
\]

Equation 4

The equation describes the conservation of energy between point 1 and point 2, where point 1 is just upstream the gate where the water level might increase or decrease depending on how much the gate is open and point 2 is at the outlet of the gate where the discharge also is dependent on how much the gate is open. The velocity at point 2 is assumed to be much greater than the rate in which the upstream water level is sinking at point 1. Therefore, the velocity at point 1 is assumed to be 0. Also the pressure at both point 1 and point 2 can be neglected, resulting in Equation 5 (Hendriks, 2010).

\[
v_2 = \sqrt{2 \cdot g \cdot (z_1 - z_2)}
\]

Equation 5

By multiplying the velocity at point 2 with the area of the opening the discharge can be calculated. Thus, based on documentation of the stage upstream and downstream of a sluice gate the discharge out of the structure can be calculated using Equation 6.

\[
Q = C_d \cdot A \cdot \sqrt{2 \cdot g \cdot (z_1 - z_2)}
\]

Equation 6
where $A$ is the area of the opening, $z_1$ the stage upstream and $z_2$ the stage downstream the structure. If the flow conditions are free and not submerged the discharge is independent of the tail water depth and can instead be calculated with Equation 7.

$$Q = C_d \cdot A \cdot \sqrt{2 \cdot g \cdot z_1} \quad \text{Equation 7}$$

$C_d$ in Equation 6 and Equation 7 is the discharge correction coefficient that depends on various factors such as contraction grade of the channel, friction losses, gate opening and the flow condition. The contraction grade is described by the empiric contraction coefficient $C_c$ that varies between 0.598 and 0.611 for sharp edged sluice gates. However $C_c$ is often set to 0.61 as it is hard to determine the real value in practice. Nasehi, Oskoyi and Salmasi (2006) developed an equation calculating $C_d$ using a set value of $C_c$ and empirical values of upstream and downstream water depth and gate opening (Equation 8).

$$C_d = 0.3865 \cdot \left(\frac{y_1}{b}\right)^{1.0676} \cdot \left(\frac{y_3}{b}\right)^{-1.4486} \quad \text{Equation 8}$$

where $y_1$, $y_3$ and $b$ is water levels respectively gate opening and are shown in figure 3. Equation 8 is the most simplified equation in the study of Nasehi, Oskoyi and Salmasi (2006) and Froudes number is excluded. The relationship is empirical and the $R^2$ number is 0.82.

### 3.2 Acoustic Doppler Current Profiler and WinRiver II

An acoustic doppler current profiler (ADCP) is a current meter using sound waves to measure the velocity of a moving fluid and a cross sectional area simultaneously. The instrument can be attached to the side of a boat so that the velocity profile of a stream can be determined. The instrument emits sound in the ultrasonic range and these sound signals are reflected against small particles in the water. It uses Doppler’s principle to calculate the velocity. This means that the velocity is estimated by relating the change in frequency of the source when the sound waves are moving relative to the source. The ADCP tracks the bottom of the channel simultaneously to the velocity measurements. Compared to more conventional current meters the ADCP is more accurate and provides more detailed calculations of the velocities. Moreover, determining the discharge using an ADCP is considerably less time consuming compared to when using conventional current meters (Mueller and Wagner, 2009).
Connecting a computer to the ADCP and using the software WinRiver II enables for the direct computation of the discharge. WinRiver II is a real-time discharge data collection program which operates the ADCP and creates files of the collected data. It uses the measured velocity and channel geometry information received from the ADCP to calculate the discharge. It also enables for the creation of geometry and velocity profiles of the channel as well as for example temperature profiles (Teledyne RD Instruments, 2007).

3.3 SUPPORT and EXPO3F
SAED has developed the programs SUPPORT and EXPO3F for documentation and calculation of the pumping volumes of the pumps they are managing. SUPPORT is software for creating pumping stations and describing the pump characteristics. One can also look at the characteristics of already existing pumping stations and make modifications to those. EXPO3F is a program for calculating the amount of water pumped by a station. The input to the program is the daily reading from the stage gauges upstream and downstream the station, as well as the number of pumping hours per day for each pump. With information about the area of the perimeters, the volume of water per unit area can be calculated. With additional information about the daily rainfall, the total amount of water received at each perimeter can be determined (SAED, n.d.a).
4. Methods
The water capacity was both calculated theoretically and measured with ADCP at the two main inlets of the Gorom-Lampsar river system. This was successfully done at the Ronkh structure, while some problems occurred at the G-gate. The existing irrigation capacity of the pumps in the river system and the water usage were also evaluated, in order to enable a comparison with the maximum discharge into the system. The existing irrigation capacity and the water usage were assessed using data measured by SAED and documented by local farmers.

4.1 Water capacity
The water capacity (i.e. maximum discharge) in the Gorom-Lampsar system was investigated by assessing the characteristics of the head regulators in the river delta and using mathematical equations to calculate the discharge. The characteristics of the two structures and data from stage measurements at the Ronkh structure were received from SAED. Furthermore, discharge measurements with ADCP were made to verify the calculations and make comparisons.

4.1.1 Ronkh
Stage data from both upstream and downstream the structure at Ronkh were available. In total 476 days between October 2002 and June 2012 had usable documentation. Although no information about the gate opening was available for those dates the data was used to calculate the discharge assuming all gates were open to 100 %. Thus, the stages that have occurred earlier when the gates were partly closed were expected to be possible also with completely open gates.

Equation 6 in Chapter 3.1 was used to calculate the discharge assuming submerged conditions and completely opened sluice gates. $C_d$ could not be calculated and was set to 0.61 since this coefficient was used by SAED earlier when calculating discharge in similar structures. The impact of this assumption was estimated by comparison with direct flow measures (see following section). The daily discharges, the maximum discharge and the mean discharge were calculated.

All calculations were done in Matlab and the Matlab-code can be found in Appendix 1.
4.1.2 G-Gate
At the G-gate structure upstream stage data was not available and therefore it was not possible to calculate the water capacity there. The only theoretical information available was that when planning for the structure the aim was for it to have a capacity of 20 m$^3$/s (Dia, 2013).

4.1.3 Measurements with ADCP
To validate the calculations, field measurements of the discharge at the two head regulators were conducted. On the 2nd of July 2013 the measurements were carried out next to the structures of Ronkh. The measurements were carried out using an ADCP attached to a boat at a water depth of 20 cm (Figure 4). The velocity profiles were created by moving the boat across a channel section close to the structure. The measurements were commenced and ended approximately three meters from the channel banks and the same section was measured approximately four times to ensure statistical adequacy. During the measurements the ADCP was connected to a laptop and the WinRiver II program was used to calculate the discharge simultaneously while doing the measurements. The compilation of the data recorded in field involved removal of outliers and generation of tables of the recorded and calculated data in WinRiver.

![Figure 4. Discharge measurement using ADCP.](image)

Similar measurements were done at Ronkh by the staff at SAED at three earlier occasions. Data from those measurements were also used in this study.

To be able to compare the calculations with the measurements, the discharge was calculated for the days when measurements were done using documented stage and gate opening data
and by using Equation 6 in Chapter 3.1. These calculations were made in the Matlab-code mentioned above (Appendix 1).

4.2 Existing irrigation capacity
The existing irrigation capacity was investigated by an assessment of the pumping stations in the Gorom-Lampsar river delta (Figure 5 and Figure 6). The locations and capacities of the pumps were evaluated by studying available documents and literature at SAED. The number of pumps and their respective capacities were compiled in an Excel document. In Excel the total water usage in m$^3$/s from each pumping station was calculated. These numbers were summarized for each channel reach. For some of the smaller pumping stations there was no available information about their pumping capacity. However, information about the number of pumps of different types and their respective irrigation areas were found. This information was used to estimate the pumping capacities for the pumps that were fairly-well documented. The total irrigation capacity was calculated by summarizing the pumping capacities of all stations in all channels.

Figure 5. Small pumping station in the Lampsar.
4.3 Water usage
In this project it was not possible to investigate the actual water usage in all perimeters in the Gorom-Lampsar river delta. Only one perimeter in the system was investigated, namely the NDiaye perimeter. The Boundoum perimeter which lies just outside the system was also investigated. The reason to why these two perimeters were investigated was that they were the only two perimeters of which pumping data was available in this study. The NDiaye perimeter is located along the left bank of the Lampsar next to the village of NDiaye, 30 kilometers north-east of Saint-Louis (Figure 7). It composes an area of 224 ha (Dia, 2013) and receives its water from the Lampsar. The Boundoum perimeter is located at a distance of 15 kilometers from the Senegal River next to the village of Boundoum, 70 kilometers north-east of Saint-Louis (Figure 7). It composes an area of 3295 ha (SAED, 2012) and receives its water from the Senegal River. The Boundoum perimeter is thus not irrigated by the Gorom-Lampsar system. Since information about the irrigation of this perimeter was available, it was included in this study to get a clearer idea of the water usage in the perimeters in the region.
The number of pumping hours for the pumps used for irrigation of the perimeters is documented daily by station attendants. The record of these data for the dry and hot season of 2013 was received for the two perimeters investigated in this study. The pumping stations and the pump characteristics were added to SUPPORT and the data record received was compiled in EXPO3F. In EXPO3F the total volume of pumped water and the number of pumping hours for each perimeter and campaign was calculated. The areas of the cultivated surfaces in the two perimeters were received from Dia (2013) for the investigated campaign. The pumped volume of water per hectare of cultivated land was calculated by dividing the volume received from EXPO3F by the cultivated area.

To estimate the water usage in all the perimeters in the Gorom-Lampsar system, information about the cultivated surface of each perimeter in the system was compiled. This data was found in SAED documentation from 2009. The assessment of the total water usage was done by comparing the cultivated surfaces in NDiaye and Boundoum with the total cultivated
surface. This was done for the two perimeters separately, according to Equation 8, and then the mean of the two calculations was determined.

\[ Q_{\text{Use}} = \frac{A_{\text{Tot}}}{A_{\text{Perimeter}}} \cdot Q_{\text{Use,Perimeter}} \quad \text{Equation 9} \]

In Equation 9, \( Q_{\text{Use}} \) is the water usage converted to include the entire Gorom-Lampsar system, \( A_{\text{Tot}} \) the total area of all the cultivated perimeters irrigated by the Gorom-Lampsar system, \( A_{\text{Perimeter}} \) the cultivated area in the NDiaye or the Boundoum perimeter and \( Q_{\text{Use,Perimeter}} \) the water usage in the NDiaye or the Boundoum perimeter.

In this investigation it was assumed that the water usage in NDiaye and Boundoum perimeters were representative for all the perimeters. The result was compared with the water and irrigation capacity of the Gorom-Lampsar system (Chapter 6.1).
5. Results

5.1 Maximum water capacity

5.1.1 Ronkh

Figure 8 shows the stage data at Ronkh between October 2002 and June 2012. It can be seen that the difference between the upstream and downstream stage was greater before the Diama dam was built in 2003. Therefore only values from after 2003 were used in the following calculations.

![Figure 8. Water stage at the Ronkh structure from October 2002 to June 2012.](image)

The discharge at the Ronkh structure, calculated using Equation 6 for all dates from when stage data was available after 2004, is shown in Figure 9. The maximum capacity during this time was 36 m³/s and it occurred the 26th of January 2006. The mean discharge during the same time was 8.6 m³/s. A sensitivity analysis was also made. When reading and documenting the stage an error of ±2 cm was assumed to possibly occur. This error leads to a difference in the calculated discharge of ±2 m³/s.
Figure 9. Calculated discharge (m$^3$/s) at the Ronkh structure between 2004 and 2013.

The results from the discharge measurements with ADCP at the Ronkh structure are presented in Table 1.

<table>
<thead>
<tr>
<th>Run</th>
<th>River width (m)</th>
<th>Section area (m$^2$)</th>
<th>Boat velocity (m/s)</th>
<th>Measured water velocity (m/s)</th>
<th>Discharge (m$^3$/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>40.55</td>
<td>147</td>
<td>0.73</td>
<td>0.11</td>
<td>8.33</td>
</tr>
<tr>
<td>2</td>
<td>39.15</td>
<td>149</td>
<td>0.79</td>
<td>0.11</td>
<td>5.55</td>
</tr>
<tr>
<td>3</td>
<td>36.47</td>
<td>147</td>
<td>0.77</td>
<td>0.13</td>
<td>9.75</td>
</tr>
<tr>
<td>4</td>
<td>35.85</td>
<td>150</td>
<td>0.85</td>
<td>0.13</td>
<td>6.30</td>
</tr>
<tr>
<td></td>
<td>Average</td>
<td></td>
<td>0.79</td>
<td>0.12</td>
<td>7.48</td>
</tr>
</tbody>
</table>

At the time of the measurements the upstream stage was 2.35 m and the downstream stage 2.18 m. One of four gates was open to 50 %. Based on these conditions the discharge at the Ronkh structure on the 2nd of July 2013 was calculated to be 2.79 m$^3$/s. Table 2 shows the measured and calculated discharges at the Ronkh structure for four different days. Table 2 also shows the estimated values of $C_d$ back-calculated from the ACDP flow measures using Equation 6.
Table 2. Measured discharges at different dates at the Ronkh structure, the calculated discharge based on the circumstances those dates and the back calculated \(C_d\) derived using equation 6 and the measured discharges.

<table>
<thead>
<tr>
<th>Date</th>
<th>Discharge from ADCP (m(^3)/s)</th>
<th>Open gates (nr)</th>
<th>Gate opening (%)</th>
<th>Upstream stage (m)</th>
<th>Downstream stage (m)</th>
<th>Used (C_d)</th>
<th>Calculated discharge (m(^3)/s)</th>
<th>Back-calculated (C_d)</th>
</tr>
</thead>
<tbody>
<tr>
<td>20/10-2011</td>
<td>10.1</td>
<td>3</td>
<td>100</td>
<td>2.28</td>
<td>2.21</td>
<td>0.42</td>
<td>9.41</td>
<td>0.45</td>
</tr>
<tr>
<td>29/11-2011</td>
<td>8.06</td>
<td>3</td>
<td>100</td>
<td>2.23</td>
<td>2.21</td>
<td>0.41</td>
<td>4.91</td>
<td>0.67</td>
</tr>
<tr>
<td>9/4-2013</td>
<td>13.3</td>
<td>4</td>
<td>100</td>
<td>2.3</td>
<td>2.28</td>
<td>0.4</td>
<td>6.39</td>
<td>0.83</td>
</tr>
<tr>
<td>2/7-2013</td>
<td>7.48</td>
<td>1</td>
<td>50</td>
<td>2.35</td>
<td>2.18</td>
<td>0.48</td>
<td>2.79</td>
<td>1.28</td>
</tr>
</tbody>
</table>

5.1.2 G-Gate

The only theoretical information available was that when planning for the structure, the aim was for it to have a capacity of 20 m\(^3\)/s (Dia, 2013). The maximum capacity in the total Gorom-Lampsar system is therefore 61 m\(^3\)/s when including the water coming from both Ronkh (section 5.1.1) and G-Gate.

5.1.3 Calculation of the maximum potential irrigated surface

According to SAED (n.d., b) the water need of rice is 271 mm per month, which corresponds to 2710 m\(^3\)/ha/month. The pumping capacity required to satisfy the water need of rice was determined by taking into account the efficiency of the pumps and the time for irrigation. The efficiency of the pumps in the Gorom-Lampsar area is approximately 70 %. A normal amount of time for irrigation is 6 days per week and 12 hours per day (SAED, n.d., b). Taking these considerations into account the pumping rate needed to satisfy the water need is

\[
Q = \frac{N/E}{T} = \frac{2710/0.7}{4.28 \cdot 6 \cdot 12 \cdot 3600} = 0.00349 \text{ m}^3/\text{s}/\text{ha} \approx 3.5 \text{ l/s/h}
\]

where \(N\) is the crop’s water need, \(E\) the expected efficiency of the pump and \(T\) is the expected time for irrigation. In the equation 4.28 is the number of weeks per month. With an irrigation of 3.5 l/s/ha and a maximum water capacity of 61 000 l/s the maximum potential surface of irrigation, \(S_{\text{max}}\), in the Gorom-Lampsar system is

20
\[ S_{max} = \frac{61,000}{3.5} = 17,430 \text{ ha}. \]

5.2 Existing irrigation capacity
The capacities of the pumping stations are shown in Table 3, as provided by available documents and literature at SAED. The total irrigation capacity with regards to the available pumps in the Gorom-Lampsar system is approximately 42 m\(^3\)/s.

Table 3. Capacities of the pumping stations in the Gorom-Lampsar system.

<table>
<thead>
<tr>
<th>Total capacity (m(^3)/s)</th>
<th>Large stations</th>
<th>Small stations</th>
<th>Large and small stations</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Upstream Gorom</strong></td>
<td>1.96</td>
<td>10.86</td>
<td>12.82</td>
</tr>
<tr>
<td><strong>Downstream Gorom</strong></td>
<td>0</td>
<td>2.42</td>
<td>2.42</td>
</tr>
<tr>
<td><strong>Diawel</strong></td>
<td>0</td>
<td>1.33</td>
<td>1.33</td>
</tr>
<tr>
<td><strong>Kassack</strong></td>
<td>1.78</td>
<td>6.36</td>
<td>8.14</td>
</tr>
<tr>
<td><strong>Lampsar</strong></td>
<td>7.10</td>
<td>10.28</td>
<td>17.38</td>
</tr>
<tr>
<td><strong>All channels</strong></td>
<td>10.84</td>
<td>31.25</td>
<td>42.09</td>
</tr>
</tbody>
</table>

5.3 Water usage
The water volume pumped to the NDiaye and the Boundoum perimeters during the campaign investigated in this project are shown in Table 4. The table also shows the cultivated surface (Dia, 2013) of each perimeter and the calculated water volume per hectares of cultivated land. According to SAED (2006) the reference values for how much water is needed for rice cultivation are between 16,000 m\(^3\)/ha and 18,000 m\(^3\)/ha for each campaign. The values for the perimeters and campaigns investigated in this study are all under or within this range. A more detailed table of the results from the water usage investigation can be found in Appendix 2.

Table 4. Water usage in the NDiaye and the Boundoum perimeters.

<table>
<thead>
<tr>
<th>Perimeter</th>
<th>NDiaye</th>
<th>Boundoum</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pumped volume (m(^3))</td>
<td>3 184 259</td>
<td>41 874 405</td>
</tr>
<tr>
<td>Cultivated area (ha)</td>
<td>198</td>
<td>2 938</td>
</tr>
<tr>
<td>Pumped volume per cultivated area (m(^3)/ha)</td>
<td>16 082</td>
<td>14 253</td>
</tr>
<tr>
<td>Gorom-Lampsar water usage (converted) (m(^3)/s)</td>
<td>10.2</td>
<td>6.9</td>
</tr>
</tbody>
</table>

The cultivated surface in the entire Gorom-Lampsar system covers approximately 8200 ha and the total water usage in the system for the dry and hot season of 2013 was 8.6 m\(^3\)/s (calculated using Equation 9, section 4.3).
5.4 Comparison
Figure 10 shows the water capacity the existing irrigation capacity and water usage as discharge in m$^3$/s. While uncertainty is not shown explicitly in the figure, these estimates must be considered uncertain due to the simplifying assumptions and lack of data and therefore represent a first approximation. From these, it is clear that the water capacity is higher than the usage and that the usage is lower than the existing irrigation capacity in the area.

Figure 10. Comparison between water capacity, existing irrigation capacity and water usage in the Gorom-Lampsar system.
6. Discussion

6.1 Comparison of water availability and usage

The water capacity in the Gorom-Lampsar system is far above the existing pumping capacity, which implies that an expansion of the irrigation is possible, based on the first approximation presented in this current study.

The water usage for the dry and hot season of 2013 was below the higher reference value (18 000 m³/ha) for the maximum water demand of rice cultures. However, the usage in the NDiaye perimeter was slightly exceeding the lower reference value (16 000 m³/ha). Since the numbers estimated in this study are rather uncertain there is a risk that the water usage in the Gorom-Lampsar river system might exceed the reference values for the next coming campaigns in NDiaye. The total water usage in the Gorom-Lampsar system was estimated to 8.6 m³/s. This confirms the indication that the water usage was realistic. The value lies below both the water capacity of the system and the existing irrigation capacity of the pumps. When looking at the monthly values of the total usage (Appendix 2) some values are higher than 8.6 m³/s. However, none of them exceeds the water capacity or the existing irrigation capacity.

Despite the optimistic result of this study, water scarcity has earlier been experienced in the area. There are many plausible reasons for this. Losses are always a problem when dealing with large irrigation systems. Some losses are included in the calculations that this study is based on, but those occurring in the main channels are not included. Evaporation in a dry and hot climate is high and there is also a possibility that water is leaching through the channel beds. Moreover, insufficient maintenance of the channels decreases the discharge to a high extent. This problem is severe, especially far downstream from the inlets. Another possible explanation to the experienced scarcity is that the water is badly distributed in the system, so that some farmers use more water than they should, leading to a lack of water for others. As such, care must be taken when interpreting these results and considering the expansion of the current agricultural system.

6.2 Water capacity

The Gorom-Lampsar system has good potential for establishing several functional gauging stations. The system is regulated with sluice gates. At most locations with gates, it would be possible to find a relationship between discharge and stage and thus relatively easy to estimate the discharge through the gates. At this time, the stage is being documented regularly at
numerous structures in the delta. However, with extended documentation practices including both upstream and downstream stage and the gate opening, the water management could be improved. It would allow SAED to estimate the flow at several points and thus gather valuable information about the system at any time, without time consuming and expensive measurements.

As mentioned in chapter 3.1 the discharge correction coefficient ($C_d$) used in the equation for calculating the discharge is not a fixed number, but can vary within a certain range. In this study $C_d$ was calculated using equation 8 resulting in $C_d$ values between 0.35 and 0.54, with a mean value of 0.43. However, when $C_d$ was back-calculated from the discharge measurements it varied considerably between 0.45 and 1.28 (table 2). The variation of $C_d$ indicates that the calculations made in this study are very uncertain. The formula used to calculate $C_d$ is not widely used and was obviously not suitable for this location. With further investigations of the gate opening and the upstream and downstream stages, the value of the coefficient could be determined with greater reliability by using a more accurate formula. This equation contains information about current conditions, environmental factors and an empiric contraction coefficient ($C_c$) suitable for the location. The correlation coefficient could then be used in more accurate calculations of the discharge through a sluice gate. The potential impact of this is clearly demonstrated by the estimated variability in $C_d$ established when comparing flow observations with flow calculations (Table 2).

In this study the calculation of the discharge through the Ronkh structure was limited due to lack of information about the gate opening. Although the stage data comes from documentation in field, caution should be taken when analysing the results. The water levels upstream and downstream Ronkh are highly dependent on how much the sluice gates are open. It was assumed that water levels that have occurred with gates partly open also could occur when the gates are completely open, although this might not be the case. The water level downstream depends on how much water is taken for irrigation and on the regulation of the Diama dam. The fact that Diama dam has a great influence on the water levels higher up in the system was obvious when looking at the stage data from before 2004 (Figure 8). The levels downstream were overall much lower before 2004 when the dam was built. This indicates that, with the dam installed, lower values than what have arose since 2004 should not be expected for the upcoming irrigation campaign. Furthermore, higher upstream stages will probable indicate higher downstream stages. This can also be demonstrated by looking at
the stage data in Figure 8. Commonly the downstream stage is following the upstream stage and greater stage differences than have been seen before are not expected in the future. Thus, it is unlikely that the maximum water capacity is underestimated but there is a possibility that it is overestimated.

It was not possible to calculate the flow through the structure G-gate due to lack of upstream stage data. The water capacity used in this study is therefore very uncertain and can be questioned. However, the comparison shows that the water capacity is higher than the existing irrigation capacity and water usage even without the flow through G-gate. Thus, the study would give the same result independent of the inclusion of the capacity at the G-gate.

6.3 Existing irrigation capacity
Because of the lack of information regarding the pumping capacity of some of the smaller pumping stations the water usage is most likely higher than the results suggested by this project. The reason for the lack of information is that the pumping stations concerned have been installed by the farmers and that these stations are to some extent homemade (Seck, 2013). There is also a possibility that there are more pumps in the river system than SAED knows about. The reason to this is that the farmers are allowed to install smaller pumping stations without telling SAED (Dia, 2013).

6.4 Water usage
For the water usage investigation, the NDiaye and the Boundoum perimeters were presumed to be representative for the water usage in the Gorom-Lampsar system. Since the conditions in all the perimeters in the region are the same, i.e. same climate, same crop etc., it seems like a fair assumption to make and the result from the investigation is thought to be trustworthy. Different parts of the investigation were based on data from different years. The usage in the NDiaye and Boundoum perimeters was investigated for 2013 while the areas of the cultivated land for all other perimeters (used for estimating the usage in all perimeters in the Gorom-Lampsar system) were based on data from 2009. That all data in the investigation were not based on the same period of time may of course have affected the result.
7. Conclusion

The interpretation of the results presented in this study suggests that the water capacity of the Gorom-Lampsar system is greater than the existing irrigation capacity. Additionally, the irrigation capacity was not fully utilized during the last year. This implies that an expansion of the irrigated area may be possible. However, water scarcity has been experienced in the study area. Possible explanations to this are evaporation and leakage from the channel beds, insufficient maintenance and unjust distribution of the water resource. However, as the numbers resulting from this study are uncertain, caution should be taken if applying the results to the irrigation system. The water capacity could be smaller than indicated, while the existing irrigation capacity could be bigger. The calculations of the water usages in NDiaye and Boundoum perimeters are more trustworthy but the transformation of the results to represent the whole Gorom-Lampsar system is questionable. With this in mind an expansion of the irrigated area might not be possible at current conditions. However, it is thought to be possible to satisfy the demand for the next coming campaigns. This presumes proper maintenance of the channels and a fair distribution of the water. To simplify the water management in the Gorom-Lampsar system we suggest that stage gauges are installed (both upstream and downstream) at all structures in the system and that the documentation is extended to also include how much the gates are open.
8. References

8.1 Personal contact


8.2 Written and electronic sources


SAED (n.d., a). *Guide methodologique pour la realisation d’un bilan de prélevement d’eau dans un périmètre irrigué de la SAED.*


SAED (2012). *Gestion et organisation de la mise en valeur du casier de Boundoum.*


Appendix 1 – Matlab code

% This program calculates the flow through the Ronkh structure
% depending on amounts of gates that are open, how much each gate is open
% and the water level on each side of the structure.

sprintf('This program calculates the discharge through the Ronkh
structure\nbased on water height upstream and downstream,\nnumber of open
gates and how much the gates are open.\nPlease insert number of gates
that are open (max 4) and specify approximately\nhow much the gates are
open (max 100 %).\nThe open fracture should be in percent. For example if 1
gate is 25 percent open insert 1 and 25.')

% Water levels in Ronkh are loaded.
load Ronkh2.txt

% Gate openings are asked for.
m = input('Number of open gates?: ');
p = input('Opening percentage?: ')/100
h1 = input('Water level upstream Ronkh? (m): ');
h2 = input ('Water level downstream Ronkh? (m): ');

% A time array is created.
% Only values before 2004 are used in the following calculations.
Y = Ronkh2(32:end,1);
M = Ronkh2(32:end,2);
D = Ronkh2(32:end,3);
t = datenum([Y,M,D]);
time = datestr(t);

o_max = 2.55; % Maximum height of gate
w = 2.5; % Width of gate
g = 9.81; % Acceleration gravity

A = o_max * p * w; % Current area of one opening
A_max = w*o_max; % Max area of one opening

h1_vec=Ronkh2(32:end,4); % Excising stage data upstream
h2_vec=Ronkh2(32:end,5); % Excising stage data downstream
H_vec = h1_vec - h2_vec; % Difference in stage

% Calculate the maximum theoretical capacity based on existing data
for i = 1:length(H_vec)
    if H_vec(i) < 0
        H_vec(i) = 0;
    end
end

Q_vec(i) = C * A_max * sqrt(H_vec(i)*2*g)*4; % Calculate discharge for all existing stage-measure
end

Q_max = max(Q_vec); % Picks out the largest discharge
Q_mean = mean(Q_vec); % Calculates the mean discharge
TSH = timeseries(H_vec, time); % Creates a time series of the stage
TS = timeseries(Q_vec', time); % and discharge.

disp(['The maximum theoretical discharge is ' num2str(Q_max) ' m3/s'])
disp(['The mean theoretical discharge is ' num2str(Q_mean) ' m3/s'])

figure
plot(TS);
xlabel('Date')
ylabel('Discharge (m3/s)')

figure
plot(TSH)
xlabel('Date')
ylabel('Stage difference (m)')

% Calculate the discharge through the Ronkh structure for the specific conditions
C = 0.3865*(h1/2.55)^1.0676*(h2/2.55)^-1.4486; % Correlation coefficient
Q = C * A * sqrt((h1-h2)*2*g) * m;
disp(['The calculated discharge at specified conditions is ' num2str(Q) ' m3/s'])
Appendix 2 – Water usage in Boundoum and NDiaye

The water usage in the Boundoum and in the NDiaye perimeters is presented in the tables below. The Gorom-Lampsar water usage is calculated by multiplying the pumping rate per hectare with the total cultivated area of the whole Gorom-Lampsar river system. The results are presented both at a monthly basis and for the whole season.

Table 1. Monthly and total water usage in the Boundoum perimeter for the hot and dry season of 2013.

<table>
<thead>
<tr>
<th>Boundoum (2938 ha) 2013, hot dry season</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pumped volume (m$^3$)</td>
</tr>
<tr>
<td>-----------------------------------------</td>
</tr>
<tr>
<td>Mars</td>
</tr>
<tr>
<td>April</td>
</tr>
<tr>
<td>May</td>
</tr>
<tr>
<td>June</td>
</tr>
<tr>
<td>July</td>
</tr>
<tr>
<td>Complete season</td>
</tr>
</tbody>
</table>
Table 1. The monthly and total water usage in the NDiaye perimeter for the hot and dry season of 2013.

*Ndìaye (198 ha) 2013, hot dry season*

<table>
<thead>
<tr>
<th></th>
<th>Pumped volume (m³)</th>
<th>Pumping time (h)</th>
<th>Pumped volume per cultivated area (m³/ha)</th>
<th>Pumping rate per hectare (m³/s/ha)</th>
<th>Gorom-Lampsar water usage (converted) (m³/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>February</td>
<td>373939</td>
<td>421</td>
<td>1889</td>
<td>0.00125</td>
<td>10.22</td>
</tr>
<tr>
<td>Mars</td>
<td>858906</td>
<td>967</td>
<td>4338</td>
<td>0.00125</td>
<td>10.22</td>
</tr>
<tr>
<td>April</td>
<td>718569</td>
<td>811</td>
<td>3629</td>
<td>0.00124</td>
<td>10.19</td>
</tr>
<tr>
<td>May</td>
<td>803836</td>
<td>903</td>
<td>4060</td>
<td>0.00125</td>
<td>10.24</td>
</tr>
<tr>
<td>June</td>
<td>397033</td>
<td>447</td>
<td>2005</td>
<td>0.00125</td>
<td>10.22</td>
</tr>
<tr>
<td>July</td>
<td>31976</td>
<td>36</td>
<td>161</td>
<td>0.00125</td>
<td>10.22</td>
</tr>
<tr>
<td>Complete season</td>
<td>3184259</td>
<td>3585</td>
<td>16082</td>
<td>0.00125</td>
<td>10.22</td>
</tr>
</tbody>
</table>