Geophysical Characterization of Waterlogging Phenomenon at Merowe – Sudan

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Abstract- Merowe town and the surrounding irrigated agricultural scheme have been affected by a severe waterlogging phenomenon, which has led to the collapse of numerous residential structures. This study aims to investigate the causes of groundwater table rise to near-surface levels and to propose appropriate mitigation measures. A geoelectrical investigation using the Vertical Electrical Sounding (VES) method was conducted and integrated with hydrogeological assessments and an evaluation of irrigation practices in the study area. The geology of the area is dominated by the Nubian Sandstone Formation, which is overlain by Quaternary to Recent sediments including Nile silt, alluvial deposits, and aeolian (wind-blown) sediments. Geophysical investigations indicate that the principal aquifer system comprises alluvial deposits consisting predominantly of sand, silt, and gravel, with a thickness generally of less than 10 m and resistivity values ranging from 300 to 1000 Ω·m. Underlain by pebbly sandstone and coarse- to medium-grained sandstone units, with thicknesses ranging from 20 to 50 m and resistivity values between 80 and 300 Ω·m. These sandstone units are intermittently interbedded with mudstone layers exhibiting resistivity values of less than 20 Ω·m. The Sum of Excess Water index revealed that the northern part of the study is very poorly drained. Surface water accumulation resulting from excessive irrigation is enhanced by the prevailing geological structure, which restricts effective subsurface drainage and consequently leads to a rise in the groundwater table. To mitigate these conditions, the study recommends improving irrigation management within the agricultural scheme. Integrated irrigation management, combining controlled surface canal irrigation with groundwater abstraction, is suggested as an effective strategy.

Index Terms: **Geophysical methods, Groundwater abstraction, Irrigation management, Nubian Sandstone, Waterlogging.**

المستخلص-- **مدينة مروي يحيط بها مشروع زراعي تعرضت المناطق المتاخمة له لظاهرة ارتفاع منسوب المياه الجوفية مما ادى الى انهيار العديد من المنازل. تهدف هذه الورقة الى دراسة هذه الظاهرة وايجاد حلول عملية والحد من نواتجها. تم استخدام وسائل بحث جيوفيزيائية وهيدروجيولوجية كما تمت دراسة وسائل وطرق الري في المشروع لفهم الجوانب المختلفة للمشكلة. اظهرت نتائج البحث ان الخزان الجوفي بمنطقة الدراسة يتكون من طبقات من حجر الرمل النوبي يشمل احجام خشنة الى متوسطة مختلطة بنوعية من الحجر الطيني. واظهرت الدراسة أن نظام الحوض الجوفي يتكون من رسوبيات تشمل الرمل والغرين والحصى بسمك أقل من 10 امتار وقيمة موصلية كهربية تتراوح من 300 الى 1000 أوم. متر تليها طبقة من الحجر الرملي تتراوح موصليته الكهربية من 80 الى 300 أوم. متر تتخللها طبقات من الحجر الطيني موصليتها الكهربية 20 أوم. متر .تسرب المياه السطحية من قنوات المشروع وفائض مياه الري أدى الى تراكم المياه الجوفية، ساعد في ذلك طبيعة التكوين الجيولوجي للمنطقة الذي لا يعمل على تصريف المياه في باطن الارض مما يؤدي ارتفاع منسوب الماء الجوفي. بناءاً على حدوث هذا التراكم لابد من مراجعة تصميم منظومة الري للمشروع واصلاح الخلل بها وإعادة تأهيلها. كما يجب تغيير إدارة نظام الري السطحي بالمشروع. اضافة الى ضرورة استخدام الري التكاملي باستغلال تراكم المياه الجوفية.**

I. Introduction

The characteristics of the interface between land and water course are still not properly understood due to high variability of subsurface properties. Geophysical methods always reveal simple techniques to predict variations in soil properties at a high resolution across various spatio-temporal scales [1]. Water flow into farmland may result in subsurface water storage, which may cause waterlogging in the area. Consequently, salts accumulate on the ground surface as deposits. This accumulation will lead to a waterlogging phenomenon. In turn, a high water-table rise near the ground surface may lead to bad cases.

The risk of land waterlogging is related to aquifer formation and soil composition. The large damaging soil and widespread processes include organic matter decline, erosion, compaction, nutrient leaching, crust formation, and waterlogging. Compacted soil can cause adverse changes during periods of excess moisture; the soil becomes waterlogged. In heavy soils, surface water accumulates on the soil surface, similarly saturating both higher and lower soil locations. These features may be classified as bad drainage of overland flow, which increases the percolation rate and then raises the water table. Seepage of water from bad irrigation conveyance also significantly increases water quantities in the aquifer[2,3]. Waterlogging over several time periods and at different soil depths can be integrated by the Sum of Excess Water that occurs each day in the primary root zone of the top 30 cm soil layer (SEW30) [4]. SEW30 is the sum of all daily values (in centimetres) by which the water table is closer than 30 cm to the soil surface (in units of centimetres days).

Table 1: Waterlogging Classes Using the SEW30 Index [4]

Waterlogging class	SEW30 Index
Well drained	< 30
Moderately well drained	30 - 100
Moderately drained	100 - 250
Imperfectly drained	250 - 500
Moderately poorly drained	500 - 1200
Poorly drained	1200 - 2500
Very poorly drained	> 2500

Aquifer characterization is a decisive technique, specifically in regions where it continuously depletes and deteriorates with time. Previous studies have used geophysical, geological mapping, and geophysical borehole logging techniques to assess the lithology of the aquifer and its impact on groundwater flow.

Previous literature presented the benefits of artificial intelligence and modern technologies in the course of waterlogged channels [5,6]. In most cases, they coincide with their counterparts of Geographical Information System and Digital Elevation Model. Recent satellite images show that the downstream of these channels is partially occupied by water ponds. The geomorphology of closed drainage basins has to be considered when planning for new cultivation in dry land catchments to better control waterlogging hazard. Accordingly, several management strategies can be adopted to combat land degradation by waterlogging [7-12].

Previous hydrogeological studies of Merowe town presented water table level rise, with annual accumulation estimated as 1 to 1.8 m. The study indicated that the waterlogging phenomenon was facilitated by the geological and hydrogeological settings of the area, with the presence of impervious layers underlying the upper aquifer. Representation of waterlogging spread over Merowe and adjacent agricultural schemes during the last decade was explored in a hazard map [13, 14].

This paper aims to investigate subsurface water accumulation in Merowe town, northern Sudan, as it impacts the surrounding agricultural farms, due to irrigation practices. The study aims to answer why this waterlogging phenomenon occurs. This phenomenon is assumed to be occurred as a lack of or weak subsurface drainage due formation of the aquifer along the Nile bank extending eastward. To verify that, a geophysical investigation was conducted along the river side and Oblique to the Nile. The novelty of this study lies in its integrated approach to investigate waterlogging by combining geophysical, hydrogeological, and appraisal of irrigation methods and practices over the cultivated area. Study relationship between surface water and groundwater could give a better understanding of the waterlogging phenomenon.

II. Materials And Methods

Merowe town is located in the Northern State of Sudan, approximately 390 km north of Khartoum and about 30 km from the Merowe Dam site. The study area includes the Lar Agricultural Scheme situated near the town, 18°29′20″N 31°49′50″E, shown in Figure 1

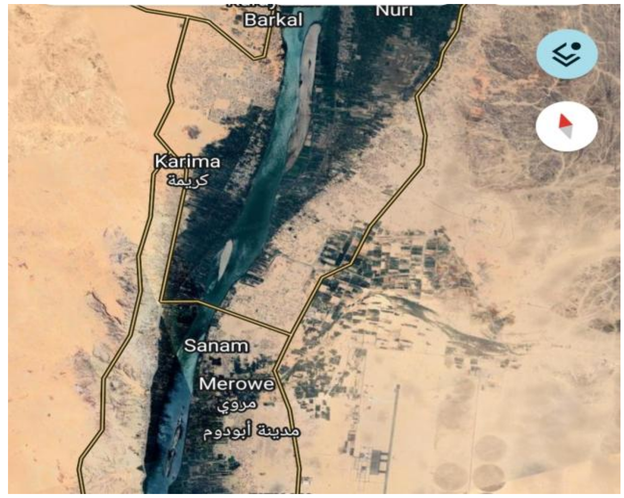

Fig. 1. Merowe town and adjacent Lar agricultural scheme

Two main morphological and lithological domains can be distinguished within the study area at Merowe: the Nubian Sandstone Formation domain and the Nile alluvial domain. The terrain is generally flat, with localized elevated areas exceeding 400 m above sea level, represented by isolated hills in the southeastern part of the study area that rise above the surrounding peneplain. In contrast, the lowest elevation, approximately 215 m above sea level, occurs along the River Nile and its associated floodplain in the western part of the area.

Most of the study area lies within an elevation range of 250–300 m above sea level, with an average surface gradient of about 0.004 toward the River Nile. The River Nile represents the principal drainage feature and flows from northeast to southwest within the study area, which contrasts with the general regional flow direction of the Nile from south to north. The local drainage network is mainly represented by Khor Abudom and several smaller seasonal streams (khors), which generally flow from southeast to northwest.

The geological framework of the area consists of Precambrian crystalline basement rocks overlain by the Cretaceous Nubian Sandstone Formation, in addition to Quaternary to Recent alluvial and aeolian superficial sediments [15, 16].

A geological map of the Northern State was used as a primary reference for investigating the geological setting of the study area. The local drainage system is represented by Khor Abudom and other small khors which generally flow from southeast to northwest. Further detailed geological and hydrogeological information sources were conducted [17 – 19].

The well inventory survey previously conducted was used to collect various hydrogeological data from the study area. In addition, a geophysical investigation was carried out using the electrical resistivity method, specifically the Vertical Electrical Sounding (VES) technique. Based on geological and hydrogeological reconnaissance and field constraints, eight VES stations were established across the study area. The measurements were performed with a sensitive SAS 1000 Terrameter, using a Schlumberger array with a maximum spread distance AB/2 < 700 m. The coordinates of each sounding location were determined using a Global Positioning System (GPS).

The acquired geophysical data were processed and interpreted using the IX-1D software, an interactive and graphically oriented inverse modeling program designed for the interpretation of resistivity sounding data based on a one-dimensional (1-D) layered earth model. The geoelectrical data were interpreted using inversion techniques to obtain a reliable subsurface resistivity model. The quality of the inversion results was assessed using the Root Mean Square (RMS) error, and an RMS misfit of less than 10% was achieved.

Geographic Information System (GIS) software was utilized for the preparation and presentation of various thematic maps related to the study. The base map, shown in Figure 2, shows data collection points prepared on a satellite image.

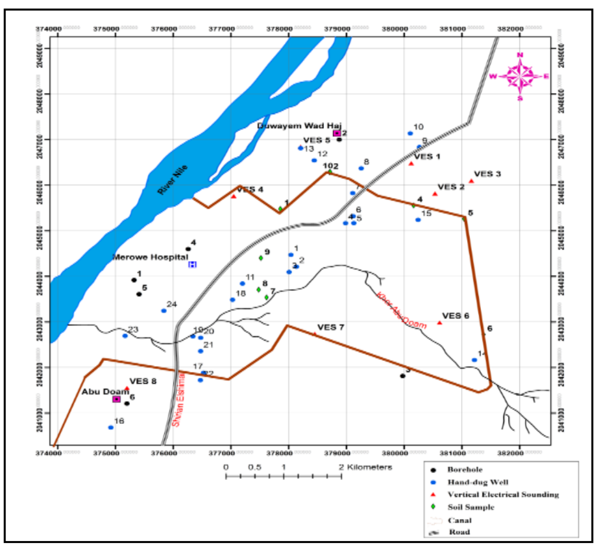

Figure 2. Data collection points.

III. Results And Discussions

Borehole data and geoelectrical investigations indicate that the groundwater system in the study area comprises multiple aquifers, each with distinct stratigraphic units and hydraulic properties. Table 2 summarizes the geoelectrical lithology and resistivity. Figure 3 represents the lithology of one of the boreholes.

Table 2 Geoelectrical lithology and resistivity

Lithology	**Resistivity Range (Ω·m)**
Superficial Deposits	10-1100
Sand	300 - 700
Gravel	400 - 1000
Mudstone	8 - 20
Gravely Sandstone	350 - 500
Clayey Sandstone	40 - 60
Sandy Mudstone	25 - 35
Coarse Grained Sandstone	200 - 300
Medium Grained Sandstone	80 - 150
Basement Complex	250 - 9000

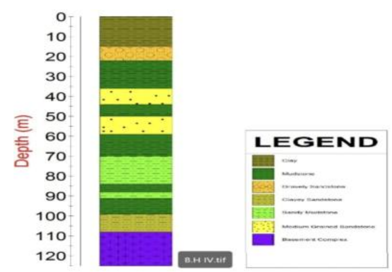

Fig. 3. Lithology of borehole IV

The study area has experienced a significant rise in groundwater levels over the past decade, primarily as a result of continuous recharge from seepage associated with the main irrigation canal and irrigated agricultural fields. This persistent recharge has led to the development of waterlogging conditions, particularly in low-lying areas such as Al-Rejila, located north of Merowe. SEW30 index was found to be > 2500 cm. days around the monitored low area; thus, that part of the study area is classified as very poorly drained since the water table is present as a swamp all the time.

Figure 4 is composed of sec. I and sec. II, which illustrate two geological cross-sections: the first extends north–south, nearly parallel to the Nile River, whereas the second extends northwest–southeast, oblique to the river course. These cross-sections provide a conceptual representation of the subsurface stratigraphy and the spatial distribution of the aquifer system.

The upper hydrostratigraphic unit, which is only a few meters thick, acts as an aquitard within the unsaturated (aeration) zone. This unit consists predominantly of Quaternary sediments, including pebbly sand, sand, and silt. The lower part of this layer is nearly saturated due to capillary rise from the underlying groundwater table. In some locations, capillary moisture reaches the land surface, producing visible wet zones that are often accompanied by salt accumulation resulting from evaporation.

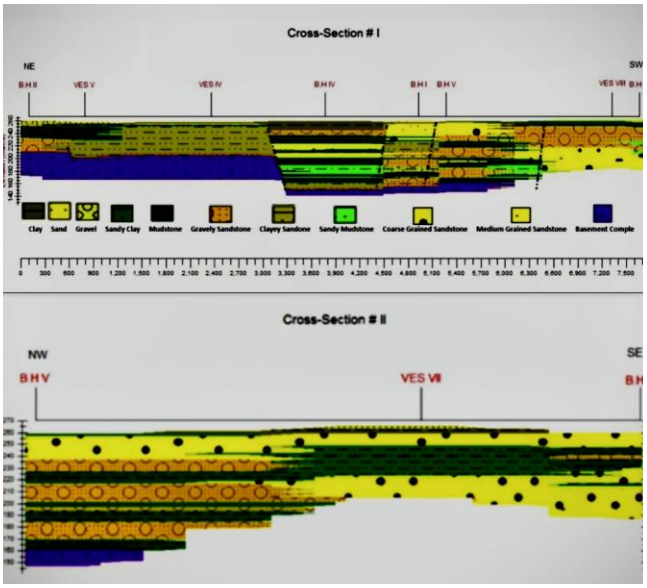

Fig. 4 Geological cross-sections

Geoelectrical data, interpreted together with borehole lithological logs, indicate that the main aquifer has a thickness ranging from a few meters to several tens of meters and is underlain by basement rocks. This aquifer behaves as an unconfined (water-table) aquifer, in which the groundwater level responds directly to recharge and discharge processes. The results further suggest that the Nubian Sandstone Formation in the study area has an overall thickness of less than 100 m.

Overlying the Nubian Sandstone Formation are recent Nile alluvial deposits, composed mainly of sand, silt, and gravel. These sediments are distributed along the river banks, floodplains, and natural levees of the Nile and generally attain a thickness of less than 10 m. The alluvial deposits directly overlie the shallow Nubian Sandstone Formation and contribute to the hydraulic connection between surface water and groundwater.

A deeper aquifer occurs within the Nubian Sandstone sequence, which consists mainly of pebbly sandstone and coarse- to medium-grained sandstone, interbedded with mudstone, shale, and clayey sandstone. The intercalation of these fine-grained layers locally influences the hydraulic conductivity and groundwater movement within the formation. The geotechnical investigations support the seepage directions inferred from the geophysical measurements, confirming the hydraulic behavior of the aquifer system and the groundwater flow pattern within the study area.

IV. Conclusions

The study area has experienced a noticeable rise in the groundwater table over the last two decades. This rise is mainly attributed to the infiltration of irrigation water from the Lar Agricultural Scheme, through both seepage from irrigation canals and percolation from irrigated farmlands. The continuous rise in groundwater levels has ultimately led to waterlogging.

Waterlogging is particularly evident in the northern residential area of Merowe town as well as within the irrigated agricultural lands. The problem is further aggravated by the geological and hydrogeological settings of the area. The upper aquifer, composed mainly of alluvial sediments, contains intercalations of relatively impermeable layers such as clay and silt, which restrict vertical groundwater movement. Similarly, the lower aquifer includes interbedded mudstone and clayey or silty sandstone layers that reduce permeability and favor the accumulation of groundwater.

The waterlogging problem in the Merowe agricultural scheme can be mitigated by adopting several management measures. These include reducing water losses caused by seepage from irrigation canals and cultivated fields, installing lift irrigation systems, implementing an effective drainage network, and utilizing groundwater for supplementary irrigation.

ACKNOWELEDGEMENT

Authors gratefully acknowledge collaborators whose work either influenced or was explicitly incorporated into this Research project. Special thanks are due to the Administration of Scientific Research and Innovation, Ministry of Higher Education and Scientific Research, for financing the research.

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