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Water leakage investigation of micro-dam reservoirs in Mesozoic sedimentary sequences in Northern Ethiopia

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ABSTRACT

Millions of people throughout the world depend on dam reservoirs for domestic water supply, irrigation, electricity and flood protection. In the last two decades, 54 micro-dam reservoirs have been constructed in Northern Ethiopia to fight the recurrent drought and improve agricultural productivity through irrigation. However, about 60% of these micro-dam reservoirs are suffering from excessive leakage. Comprehensive studies have been carried out on two micro-dams to assess and pinpoint the causes of leakage. Arato and Hashenge micro-dams located in Northern Ethiopia have 20 m and 19 m height, and 2.59 Mm^3 and 2.23 Mm^3 reservoir capacities respectively. Observational geological description, shallow hand dug test pits, vertical electrical sounding and drilling of geotechnical holes were used to understand the overall geological, engineering geological and geo-hydrological set-up of the area. The different methods applied, such as discontinuity analysis, geophysical surveys, drilling and packer tests, delivered results that were found to be in close agreement and led to the identification of the leakage zone. The geological units found in both sites are limestone–shale–marl intercalation, dolerite and recent soil deposits. The research results revealed that the limestone–shale–marl intercalation unit is heterogeneous and shows alternating sequences. Analysis of the different data shows that the limestone–shale–marl intercalation is a pervious unit (hydraulic conductivity in the range of 10^{-4}–10^{+2} cm/s) and was found to be responsible for the excessive leakage of the micro-dams. It is hoped that the observations, data and insights gathered from these case studies will enable to plan technically and economically viable anti-leakage measures for these schemes and help for future new site selection and design activities in the region and other regions with a similar geological environment.

1. Introduction

Millions of people throughout the world depend on dams and reservoirs for domestic water supply, irrigation, electricity and flood protection. Dams require significant investments for investigation, design, building and maintenance, and yet their usefulness and integrity are constantly threatened by leakage and sedimentation. Leakage and preferential flow paths are often controlled by the geology of the site. Therefore, any leakage study should always include obtaining detailed geological and hydrogeological information as the first step.

The variability of rainfall coupled with extended duration of droughts is threatening food and water security in sub-Saharan Africa in general (De Hamer et al., 2008) and in East Africa, in particular. Construction of micro-dams in Ethiopia started in the late seventies to combat the recurrent drought in the country (Tiruneh, 2005). The construction of micro-dam reservoirs in arid and semi-arid areas like in Northern Ethiopia, where the main socio-economic activity is rain fed agriculture directly linked to the erratic and variable rainfall in time and space (Yazew, 2005; Walraevens et al., 2009), is quite important. The northern part of the country, particularly the area around Mekelle Outlier, is drained by intermittent rivers, which are dry 8–9 months of the year (Nedaw and Walraevens, 2009). From the perspectives of food security and poverty reduction, the construction of micro-dam reservoirs, to ensure dry season water availability, is crucial. In the last two decades, about 54 micro-dams have been constructed in Northern Ethiopia for irrigation and domestic purposes (Haregeweyn et al., 2006).

Since 1992, the Commission for Sustainable Agriculture and Environmental Rehabilitation in Tigray (COSAERT), responsible for constructing micro-dam reservoirs, has been established. Since its establishment, up to 54 micro-dam reservoirs have been constructed in Northern Ethiopia by COSAERT and later on also by other organizations, most of which are located in the sedimentary

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basin of Mekelle Outlier. However, due to technical and operational problems, most of the micro-dams are not operating as planned objectives (Abdulkadir, 2009; Berhane, 2010a; Desta, 2005; Gonzalez-Quijano, 2006; Haregeweyn et al., 2005, 2006; Nedaw and Walraevens, 2009) (Table 1).

Most of the micro-dam reservoirs are under risk of insufficient inflow (actual flow less than designed flow), excessive leakage and sedimentation (sediment yield much higher than expected) and some of them have structural and stability problems (Abdulkadir, 2009; Haregeweyn et al., 2006). These problems are mainly attributed to the use of a poor database on hydrology and sediment yield, and lack of implementing methodologies for assessing and controlling factors at the planning, design, construction and post construction stages.

According to Haregeweyn et al. (2006), out of the constructed micro-dam reservoirs, nearly 60% of them have serious leakage problems, 61% have problems of insufficient inflow or hydrological problems and 35% have sedimentation problems, attributed to inadequate planning and lack of experiences. Moreover, a survey made on 40 micro-dam reservoirs in 2007 by Abdulkadir (2009) indicated that there are a number of problems which are affecting their performance. The assessment was made based on the United States Federal Emergency Management Agency (FEMA) dam-safety guidelines. The observed problems were insufficient inflow, leakage, sedimentation and dam stability. The seepage quantity estimated by COSAERT based on records made in successive months in 2001 varied significantly among reservoirs with the lowest being 0.27 l/s and the highest 81 l/s. Moreover, in many micro-dam reservoirs the rivers are perennial in the downstream, while ephemeral or intermittent in the upstream part. This situation indicates that a continuous leakage from the reservoir is recharging shallow aquifers and leads to emerging of new springs and increased discharge of existing ones (Tesfamichael et al., 2005; Gonzalez-Quijano, 2006).

Desta (2005) pointed out that, due to the ambitious plan of constructing as large number of micro-dams in the shortest time possible, adequate studies related to proper site selection and other pertinent investigations were not conducted. Due to this fact, water leakage has become a major problem in many of the micro-dam reservoirs (Abdulkadir, 2009; Haregeweyn et al., 2006). The leakage may be through the base, while in other cases it is through the sides and through the strata in which the reservoir was constructed.

Engineering geological investigation and mapping mainly focus towards understanding the interrelationships between the geological environment and the hydraulic structure, the nature and relationships between the geological components, the active geodynamic processes and the prognosis of processes likely to result from the changes being made (UNESCO, 1976). Even though a number of studies have been carried out related to runoff or inflow, sediment yield, ecology and health related issues of the reservoirs in Tigray (Abdulkadir, 2009; Desta, 2005; Haregeweyn et al., 2005, 2006, 2008a,b, 2011; Dejenie et al., 2008, 2009; Girmay et al., 2009), leakage and associated engineering geological and geohydrological aspects, which are critical in terms of water harvesting perspectives for existing and future reservoirs and related development plans, have not yet been touched. This paper is aiming at assessing and evaluating the engineering geological and geohydrological conditions of the dam reservoirs and at identifying the main causes of leakage. The authors hope that the representative examples of these micro-dam reservoirs in the Mekelle Outlier presented in this paper may help dam planners and decision makers in conceiving their future water harvesting and management strategies, and may call for further research on the problem.

2. Selection of study areas and statement of the problem

Hashenge and Arato micro-dams are located in the central part of the Mekelle Outlier, about 35 km east of Mekelle on the extension of the central highlands of Ethiopia (Fig. 1). The altitude of the study area ranges between 2200 m and 2660 m above mean sea level. The area is bounded by rolling mountain ranges in the east, south and north, and flat lying land to the west. The catchment or drainage area of Hashenge and Arato dams is 19.3 and 20.8 km^2. Other salient features of the two dams are presented in Table 1.

The two micro-dam reservoirs were selected by taking into account the following factors and criteria: (1) representative geological set-up of Mekelle Outlier; (2) low sedimentation problem from field observation and limited inventory by COSAERT; (3) reservoirs which have sufficient inflow; (4) availability of catchment/drainage area; (5) evidence of new springs, wetlands and increase in discharge of streams after construction; (6) availability of suitable land for irrigation and (7) possibility of rehabilitation to get benefit from the already constructed reservoirs.

Serious leakage problems were experienced since their construction and they are considered to be geologically representative of the Mesozoic sedimentary series in the Mekelle Outlier. Since the construction of these micro-dam reservoirs, following the rain season it is common to see farmers divert the leakage water, 500–900 m downstream of the reservoirs by constructing temporary traditional weirs, to their farm plots to supplement their rain fed crops. The yield of springs, new wetlands and stream discharge found downstream of dams have been increased since the construction of the dams. Such serious leakage played its part in the discrepancy between the planned or designed and actual irrigated area as illustrated in Table 1.

All dams produce seepage in different orders of magnitude and quantities. Seepage is not necessarily problematic, provided the objectives and the stability of the dam are not affected. Certain degree of leakage or seepage is accepted as long as it does not com-

Table 1
Salient features of few micro-dam reservoirs located in the sedimentary basin of Mekelle Outlier.

Name	Year of construction	UTM (zone 37) locations			Reservoir capacity (Mm^3)	Dam height (m)	Command area (ha)	
		E (m)	*N* (m)	Elevation (m)			Designed	Actual
Adi-Kenafiz	1997/1998	544,009	1,465,486	2161	0.75	15.50	60	<20
Arato[a]	1997	570,103	1,461,125	2424	2.59	20.00	120	<10
Dur-Anbessa	2000/2001	547,394	1,467,513	2133	0.13	18.00	61	<25
Gereb-Shegalu	1998	548,533	1,501,661	1921	1.00	15.33	50	<20
Gereb-Mihiz	1997/1998	550,630	1,469,662	2123	1.35	17.50	80	38
Hashenge[a]	1996	572,850	1,489,900	2400	2.23	19.00	120	11
Korir	1995/1996	566,088	1,519,994	2022	2.00	15.00	100	60
Mai-Leba	1997/1998	524,955	1,513,791	2290	0.96	19.00	50	None
Era-Quihila	1996/1997	564,560	1,486,767	2321	1.18	n.a.	87	25
Sewhi-Meda	1998	544,938	1,496,133	1995	0.36	14.50	70	None

n.a. = Data not available.
[a] Selected micro-dams for detailed study.