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REVIEW

Conservation Technology Model Fit for Farmlands in a Micro-watershed on the Ethiopian Highlands

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Abstract

The Tigray government in the Federal Democratic Republic of Ethiopia has implemented several water harvesting technologies to improve agriculture in drylands. They constructed 92 micro-dam reservoirs from 1992 to 2012. However, the sedimentation resulting from gully erosion has been settling in more than half of the micro-dam reservoirs. Consequently, it is difficult to provide the required irrigation for the upland fields situated downstream, especially in situations of decreased water availability, caused by the sedimentation over the bottom pipe intake of the irrigational systems/structures. The objectives of the present research are: 1) to verify the conservation of agriculture on farmlands situated at upper slopes for reducing erosion, 2) to estimate the sedimentation rate in micro-dam reservoirs, constructed by the local government, engineers, and residents for recycling the sediments, and 3) to cultivate vegetables on reclaimed farmland by reusing the sediments in micro-dam reservoirs. Thus, this study reports a case study of the water and soil management technology model in a micro-watershed in the Ethiopian highlands.

Discipline: Agricultural Engineering
Additional key words: bathymetric survey, micro-dam reservoirs, reclaimed farmland, sedimentation, wheat residue

Introduction

The Federal Democratic Republic of Ethiopia (hereinafter Ethiopia) is located in the eastern part of sub-Saharan Africa (North Latitude of 3° to 14° and East Longitude of 33° to 48°). Agriculture is one of its principal industries, which accounts for 31% of the total GDP (26.2 billion dollars) and 66% of the employed population (World Bank 2022). Most of the national land, which pertains to the semi-arid region, is situated on high terrain where the elevation is over 1,700 m (Suzuki 2015). The topsoil of farmlands often erodes downwardly due to water erosion during rainy season, thereby progressing the soil degradation. The population of Ethiopia, which is the second largest of African countries, is approximately 110 million, and its annual increment accounts for 2.6% (World Bank 2022). Although food production needs to be maximized as the population rate continually expands, drought often devastates Ethiopia and causes famine. Therefore, it is important to retain soil moisture in farmland to increase crop productivity. However, only 0.5% of farmlands in Ethiopia have irrigation systems (World Bank 2022), and thus, the development of irrigation is essential.

The Tigray government, which is located in the northern part of Ethiopia, promoted water harvesting technology and constructed 92 micro-dam reservoirs from 1992 to 2012. However, in the majority of the micro-dam reservoirs, sedimentation has settled due to gully erosion frequently occurring in the region (Berhane et al. 2016). In instances where the inlet of the bottom pipe in the micro-dam reservoirs has been buried in

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sediments, it is difficult to provide irrigation for the downstream upland fields; the available water in the micro-dam reservoir decreases as well. The sediment volume eroded to the downstream micro-dam reservoirs by soil erosion in a micro-watershed in Tigray was 9.09 t/ha/year (Heregeweyn et al. 2006). Therefore, sediment removal in the micro-dam reservoir that has accumulated is urgent. However, this has been unaccomplished because it is difficult to deal with the sediments under water in micro-dam reservoirs.

The authors performed a conservation agricultural test in wheat cultivation to preserve the sloping farmland located upstream of a micro-watershed in the Ethiopian highlands. Conservation agriculture technology is one of the technologies employed to mitigate the sedimentation caused by soil erosion. It is defined as a set of land management principles, including plow reduction, soil covering, and/or various crop rotational practices, toward achieving minimal soil disturbance (Kaumbutho & Kienzle 2007). The principal aim of the conservation agriculture technology is to mitigate soil erosion and soil loss by leaving the crop residues in farmlands to cover the topsoil. However, the limitation in losing wheat residue causes a threat to the livestock feed. It would be necessary to compensate the farmers in this administrative region to encourage them toward adopting the conservation agriculture technology. In cases where the soil cover ratio is more than 40%-50%, the soil erosion would be considerably reduced (Imai 1982). Hence, it is important to increase the soil cover ratio to achieve soil conservation. The authors removed the sediments, which had accumulated in the micro-dam reservoir due to soil erosion and reclaimed them on barren land near the downstream micro-dam reservoir. We also cultivated vegetables on the reclaimed farmland, which was constructed by the local government, engineers, and residents. We set three pillars for the participants: teamwork (punctuality), communication (accuracy), and leadership (practicality) based on the constructability concepts. The present research aims to develop a water/soil management model in a micro-watershed in the Ethiopian highlands by analyzing the case study of the Adizaboy micro-watershed in Tigray, Ethiopia.

Research area

A location map of the research area is shown in Figure 1. The Adizaboy micro-watershed (Area: approximately 8.5 km^2), which is located near Mekelle, Tigray, in the northern Ethiopia, was selected as the research area. The Adizaboy micro-watershed extends in the highlands with an elevation of 2,050 m-2,275 m above sea level (a.s.l.), and the area on a slope of >10° accounts for 24% of the area. The climate is characterized as semi-arid. The annual average rainfall is approximately 600 mm. The average maximum and minimum monthly temperatures equal 30°C and 8°C, respectively, which characterizes a tropical alpine climate. The topography of the micro-watershed is of a steep slope, and the terrain consists of shale, marl, and limestone (Berhane et al. 2013). The small watershed is sensitive to erosion due to the rugged topography with rocky geology. The surface soil mainly consisted of Cambisols. Large trees, such as *Acacia* spp. and *Olea europaea*, have been planted and gravels are included in grasslands and rainfed croplands. The long-term use of farmlands for crop cultivation has caused serious land degradation due to the steep topography, water erosion, and insufficient vegetation cover. Land degradation and drought have caused recurring famine. The large-scale gully erosion, which has been caused by water erosion of the topsoil, transports water and soil sediments down to the micro-dam reservoir while meandering. Cereal crops, including wheat, barley, and teff, are cultivated on dry farmland, mainly consisting of gravel. Part of the border of the micro-watershed is connected to the ditch, which has been installed beside the road. The Ethiopian government has promoted the construction of water harvesting facilities, such as micro-dam reservoirs, for more than a couple of decades. The Adizaboy micro-dam reservoir was constructed in 2009 at the exit of the Adizaboy micro-watershed. Four major gully erosions formed upstream of the micro-watershed have caused sedimentation of the Adizaboy micro-dam reservoir. Water leakage has also been a challenge due to the jointed limestone in the foundation rock.

Weather observation

The weather observation was carried out to specifically analyze the rainfall pattern in the Adizaboy micro-watershed (Fig. 1). This was performed using a weather observation device (Onset Computer Corporation), which was installed on a fence constructed with wood poles and barbed wire (4 m × 4 m × height 1.5 m) to be protected from grazing livestock (cow, goat, and sheep) during the daytime. The distance between the analytical device and the house structures was approximately 10 m to prevent the windscreen effect. The observation time interval was set to 1 h. We used a tipping-bucket rainfall gauge without any windshield. We downloaded the weather observation data stored in a data logger (HOBO U30NRC, Onset Computer Corporation) by connecting a cable to our note PC.

Figure 2 shows the rainfall observation results. The

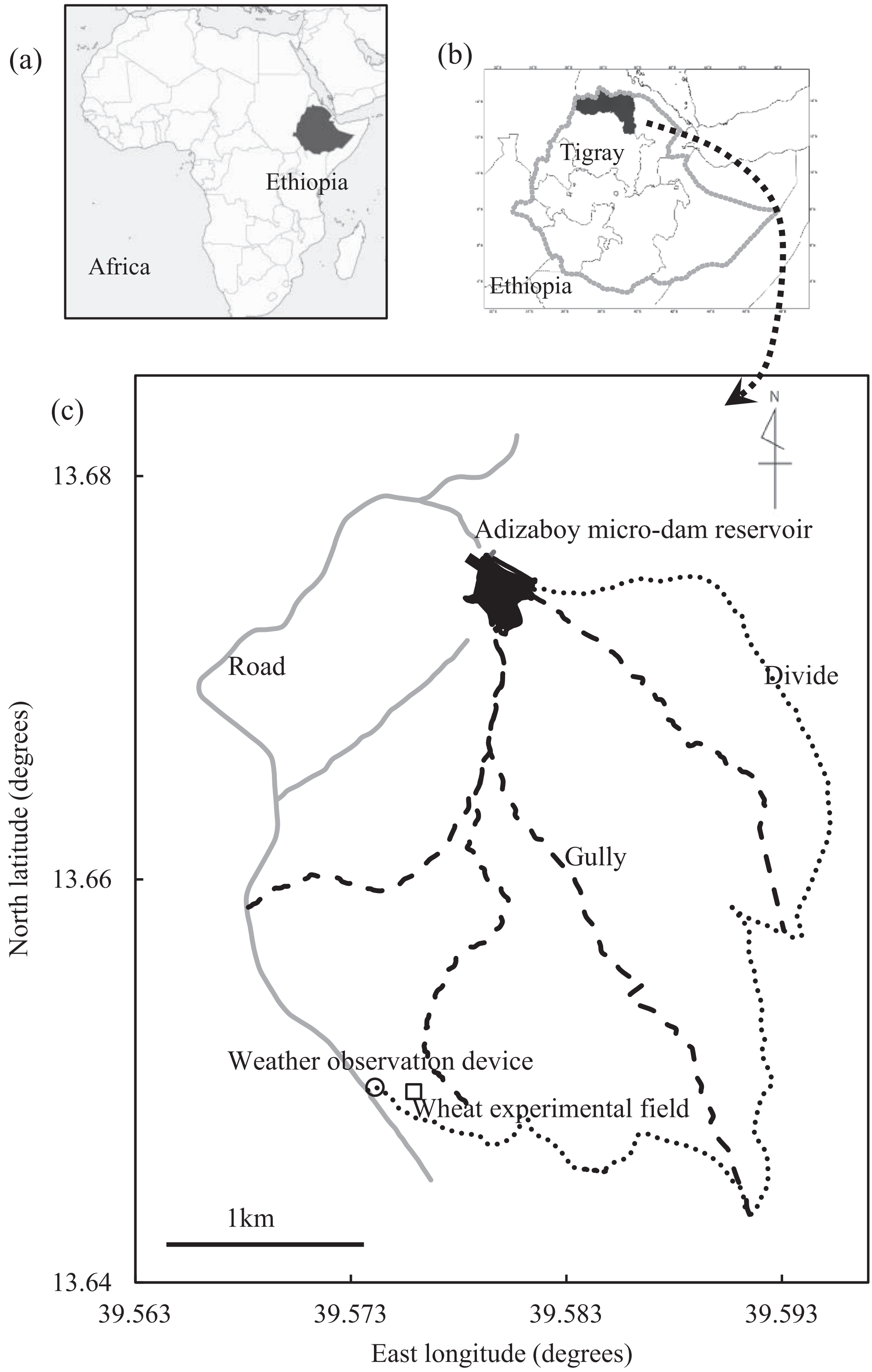


Fig. 1. Location map of the research area
(a) Ethiopia, (b) Tigray, and (c) Adizaboy micro-watershed

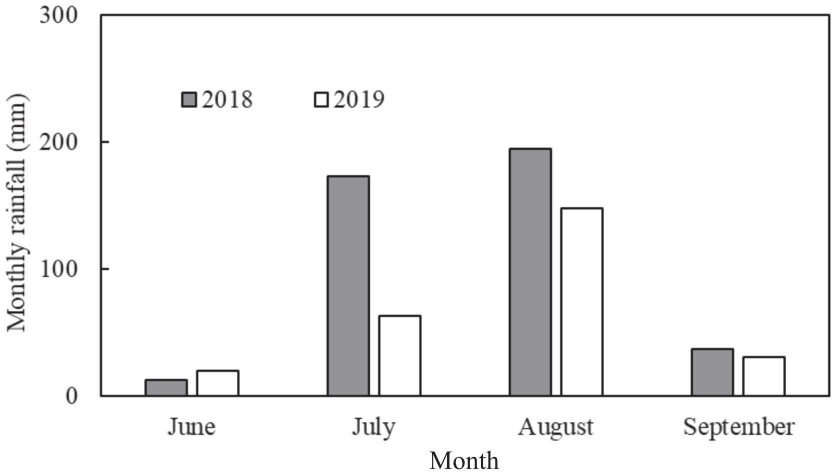


Fig. 2. Monthly rainfall during the rainy season in 2018 and 2019

average rainfall was 477 mm. The monthly rainfall during the rainy season from June to September in 2018 was 418.6 mm; that in 2019 was 261.6 mm. The rainfall in 2018 has a 3-year probability and in 2019 has a 10-year probability, according to the Hazen method.

Conservation technology of micro-watershed

1. Conservation agriculture technology

In the present research, the placement of wheat residue had been changed as a conservation agriculture technology and vetch mulching was conducted as advanced crop technology. Their yield and soil covering effects were evaluated. There were two placement methods for wheat residue: one was high-cut, and the other was low-cut. The wheat high-cut implies that the wheat stem had been cut at one-third from the wheat spike. However, the wheat low-cut means that the wheat stem had been cut at two-thirds from the wheat spike. As a control treatment, the wheat stem had also been cut near the root, and this is the conventional way to place the wheat residue on farmland. The wheat residue had not been incorporated directly into the soil. However, the nutrient was expected to emanate from the residue as it was decomposed, and the soil structure and erosion had been improved and reduced, respectively.

(1) Wheat cultivation tests on slopes

The authors carried out a level survey to draw the contour map and select the optimum site. The USLE (Universal Soil Loss Equation) experimental field's shape was rectangular, and the size was 25.7 m (along the slope) and 27.6 m (horizontal direction) in total and was reclaimed on the upstream slopes of the Adizaboy micro-watershed. The soil was fertile, and the topsoil consisted of shale mixed with clay. The soil components below the topsoil were classified as clayey Vertic Cambisols. Wheat cultivation was rainfed. In the first year (2018), conventional plowing by oxen was conducted three times. In the second year (2019), partial plowing using a hoe was conducted at 20 cm intervals on the field where the wheat and vetch (*Vicia dasycarpa* Ten.) residues of the previous season were left. The depth and width of the manual hoe plowing were about 15 cm and 10 cm, respectively. With reference to the test standard specified by USLE, the dimensions of the wheat treatment plot were 1.8 m in width, 10 m in length, and a slope of about 8%.

In 16 subplots with four replications and four treatments, including a control, a wheat cultivation test was conducted. Figure 3 shows the schematic view of the wheat cultivation test and alignment of the residue treatment. Table 1 presents the residue treatment in the conservation agriculture test on the slope. There were four residue treatments. In the first year (2018), wheat and vetch were cultivated. The residues were wheat high-cut, wheat low-cut, wheat control, and vetch mulching. In 2019, only wheat was cultivated. The study plots were wheat high-cut, wheat low-cut, and wheat control. The wheat residues (mainly straw of wheat) were left on the field.

(2) Conservation agriculture technology on a slope

Figure 4 shows the grain yield of the wheat cultivation test on the slope. We cultivated wheat and vetch in the first year and left the residue for the second year. The wheat yield in 2018 was almost the same in the four treatments because of the first cultivation and

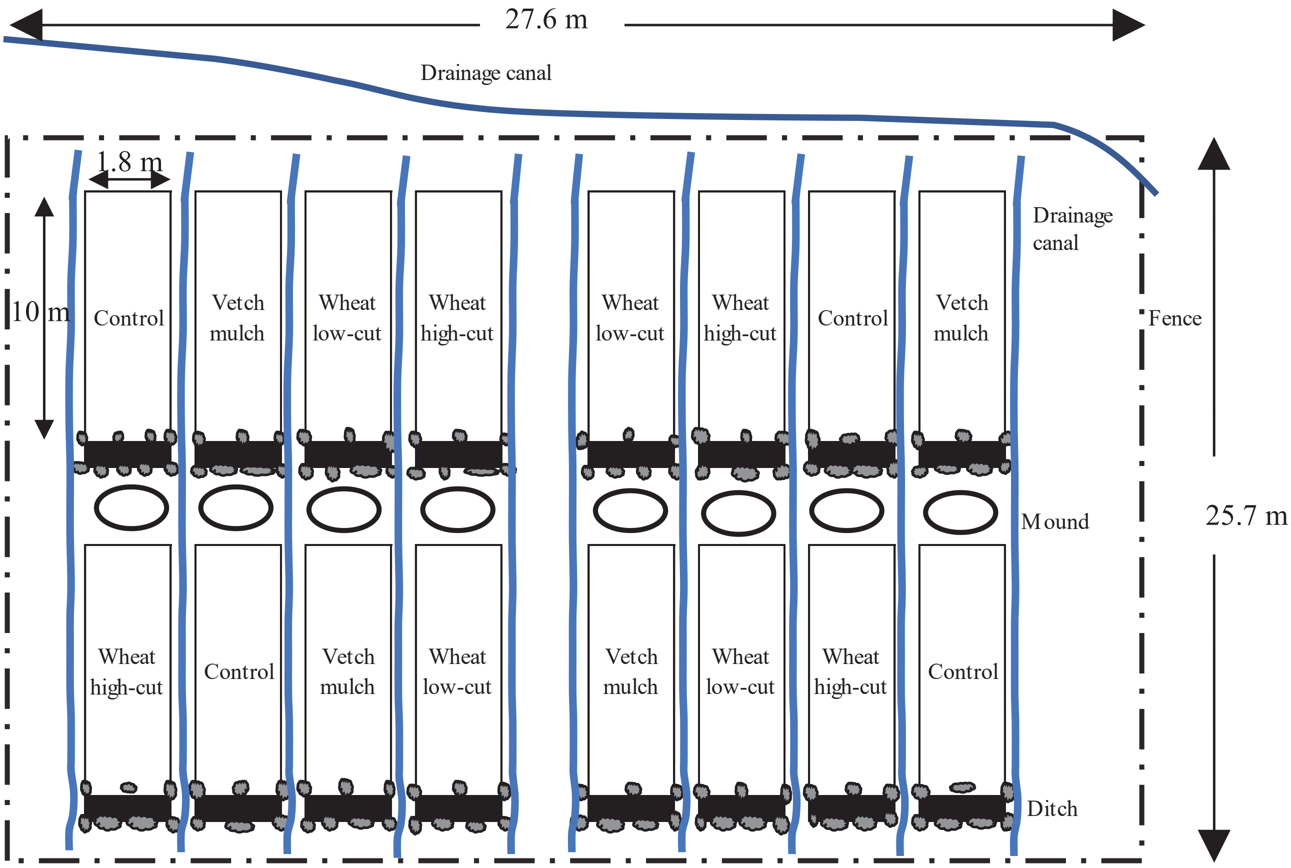


Fig. 3. Schematic view of the wheat cultivation test on a slope and alignment of the residue treatment

Table 1. Residue treatment in the conservation agriculture test on the slope

Year	Treatment 1	Treatment 2	Treatment 3	Treatment 4
2018	Control	Wheat high-cut	Wheat low-cut	Green manure (vetch mulch)
2019	Control	Wheat high-cut	Wheat low-cut	Wheat high-cut

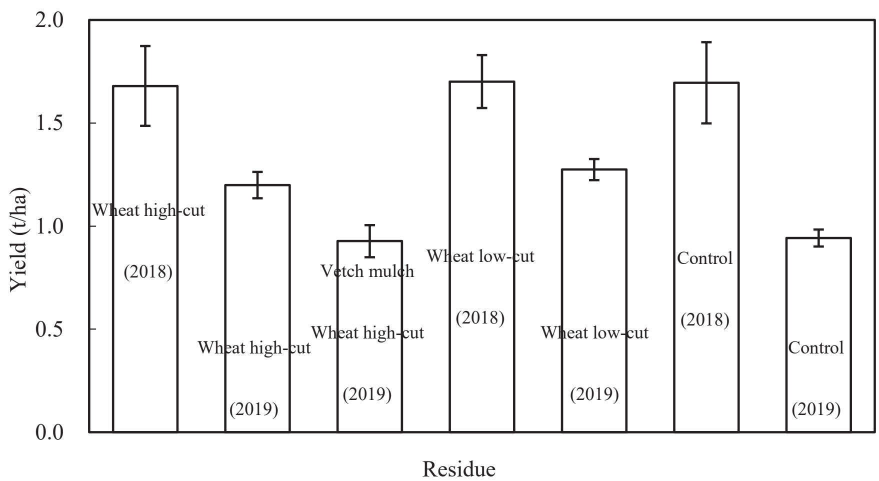


Fig. 4. Grain yield of the wheat cultivation test on the slope

there was no input used. The yield of the wheat high-cut was 1.68 t/ha while the wheat low-cut yielded 1.70 t/ha, and that of the control was 1.70 t/ha. There was no significant variation (*P*-value = 0.05). Toward the onset of the second cultivation, both the wheat residue and vetch mulching were decomposed and disappeared to certain degrees due to the dry conditions on a natural slope. The wheat yield in each treatment showed a significant difference in the second cultivation in 2019. The wheat yield of the control was 0.9 ± 0.04 t/ha, while that of the wheat high and low-cut was 1.20 ± 0.06 t/ha and 1.27 ± 0.05 t/ha, respectively. Moreover, the yield of wheat high-cut after vetch mulching was 0.93 ± 0.08 t/ha, which was almost the same as that of the control. The sequential order of the wheat yield is as thus: wheat low-cut, wheat high-cut, wheat high-cut after vetch mulching, and control. The yield obtained from this test is consistent with the general wheat yield in northern Ethiopia, which ranges from 0.4 to 4.1 t/ha (average 1.5 t/ha) (Silva et al. 2021).

A ladder was installed to take photographs of the soil cover from a height of 2 m in each subplot, prior to the wheat seeding. Binary pictures were taken and analyzed by using Image J (National Institute of Health) to separate the wheat and vetch residue cover from the soil. The soil cover ratio, which can serve as an index of soil erosion, was then calculated. Conservation agriculture technology was evaluated using this parameter. Although we were planning to measure the amount of soil erosion and water, the total amount of soil erosion could not be measured because some part of the soil flowed down into the ditch covered by the blue sheet. Due to the insufficient design of the field experiment, we used an indirect parameter to evaluate the potential erodibility of the study plots. A significant difference in the soil cover ratio was observed in each treatment in the second cultivation in 2019. The soil cover ratio of the control was 34.7 ± 1.0%; that of the wheat high-cut was 38.1 ± 0.8%; the wheat low-cut was 38.0 ± 0.7%; finally, that of the wheat high-cut after vetch mulching was 37.2 ± 0.7%. The sequential order of the soil cover ratio was: wheat high-cut, wheat low-cut, and wheat high-cut after vetch mulching, and control.

The amount of rainfall during the rainy season in the Adizaboy micro-watershed decreased from 418.6 mm to 261.6 mm in 2018 to 2019, respectively. Notably, 2019 was the drought year. The lapse in wheat yield in 2019 was attributed to the decreased rainfall, caused by drought. The wheat yield of the vetch-covered plot was lower than that of the plots covered by wheat residues, implying that the effect induced by the vetch was minimal. Notably, vetch readily decomposes due to its small C/N ratio. We would like to point out that 1) the wheat yield brought by vetch mulching was almost the same as the control, and 2) we also visually confirmed that the wheat growth near the ditch was comparatively larger because the surrounding water was clogged. The critical factor that controlled the wheat growth on a slope was the soil moisture, rather than the nitrogen fixed by vetch.

2. Sustainability of the micro-dam reservoir technology

(1) Structure of the Adizaboy micro-dam reservoir

The Adizaboy micro-dam reservoir is classified under the zone type “rockfill dam,” which is situated downstream of the micro-watershed constructed in 2009. The crest length was 276 m, the embankment height was 7.01 m, and the storage volume was 0.2 million m^3, which are smaller than the average measurements of 92 micro-dam reservoirs constructed in Tigray (crest length of 373 m and embankment height of 16 m) (Berhane et al. 2013). During drought, the micro-dam reservoir dried prior to the end of the dry season. There is a spillway on the right-hand side of the sloped natural terrain, which leads to the flood bypass. The bottom pipe contains the inlet, which is located toward the deep-end/depth of the micro-dam reservoir, and has been coupled with a metal filter. The outlet of the bottom pipe had a butterfly-shaped valve. The micro-dam reservoir has been employed for livestock drinking, individual/personal use, and irrigation purposes.

(2) Available water amount

A GPS (GPSmap 60CSx, Garmin Ltd.) was used to obtain information on the location of the survey points. We used a level (GOL 26D Professional, Bosch GmbH) in conjunction with a leveling staff to measure the height differences from the tentative benchmark. The reservoir storage volume was calculated using Surfer Ver. 22 (Golden Software Inc.).

Stored water in the Adizaboy micro-dam reservoir has been used for irrigation in the upland fields to cultivate tomatoes, garlic, onion, etc. The available amount of irrigation water for the reclaimed farmland was estimated by using the water balance equation of the micro-dam reservoir. The utilization of water storage was predominant in the downstream upland irrigation due to the water rights, which have already been possessed by farmers. However, the utilization of the water storage for irrigating the reclaimed farmland was achieved by the water balance analysis. Notably, if the stored water in the micro-dam reservoir dries up during drought, it was possible to transport the groundwater in Wukro to the farm pond in the reclaimed farmland as an emergency water source by using a water supply truck.

(3) The volume of sediments

The sedimentation in the Adizaboy micro-dam reservoir has been settling since its construction. The results obtained from soil analysis had shown that the sediments mainly contained potassium and had a potential for crop growth (Koda et al. 2019). However, the depth of sediments was not observed when the construction of the Adizaboy micro-dam reservoir was completed. We adopted the new bathymetric survey method using an echo sounder (HE-8301F-Di, Honda Electronics Co. Ltd.) attached to the boat in the micro-dam. We obtained the sediment surface data generated by the echo sounder and compared the depth with the 85 observation points described in Figure 5 in November 2017 with the results of the actual measurement and further confirmed the accuracy using a survey staff. The authors used the software of Surfer Ver.22 to interpolate the bottom of the pond by the point data and to calculate the volume of sediments, which is located between the sediment surface and bottom.

A time-dependent survey for the storage area (coordination and water depth) and sediment surface depth was conducted in the Adizaboy micro-dam reservoir from September 2016 to November 2017. The depth of the sediments was estimated. The estimated depth was consistent with the bottom pipe depth obtained from the level survey, which confirmed the accuracy of

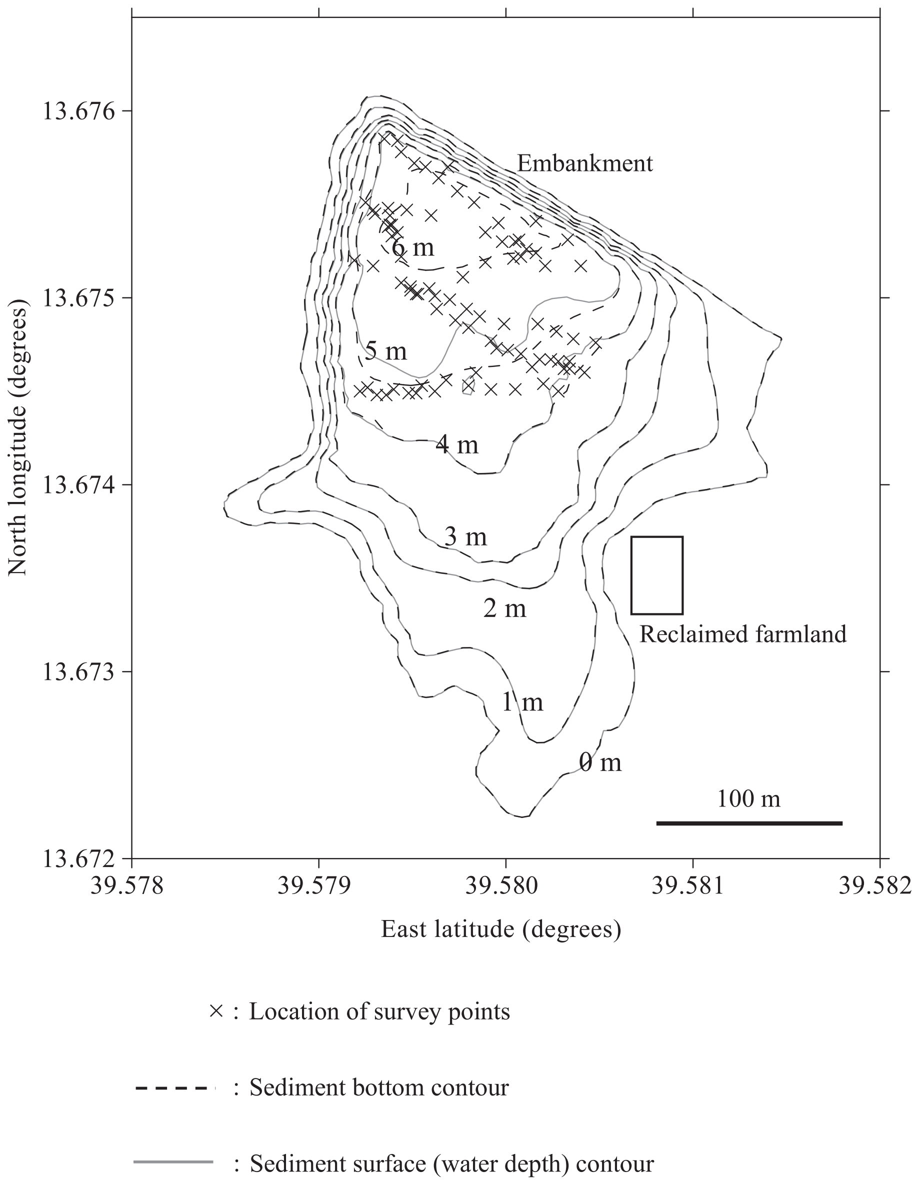


Fig. 5. Contour map of the micro-dam reservoir sediment surface and bottom

the estimation. The contour map of the micro-dam reservoir sediment surface and bottom depth is shown in Figure 5, which indicates the sediment surface depth measured by the echo sounder; the sediment bottom depth was estimated by time-series observation in the micro-dam reservoir. The figure also expresses the location of the survey points conducted using an echo sounder in the Adizaboy micro-dam reservoir. The results show that the average area of the micro-dam reservoir was approximately 35,700 m^2; the sediment depth of this area was interpolated as 0.18 m, and the sediment volume was evaluated as 6,400 m^3 (Koda et al. 2019). If the thickness of the soil surface layer of the reclaimed farmland equals 0.2 m, then the reclaimed farmland area equals 3.2 ha, using sediments in the micro-dam reservoir. Hence, it is important to estimate the study area to enhance future agricultural rural planning.

3. Food increased technology

(1) Adoption of constructability

At the end of the dry season in the Adizaboy micro-dam reservoir, the sediments beside the bottom pipe were removed in collaboration with Japan International Research Center for Agricultural Sciences (JIRCAS), Mekelle University, and the Agulae village office. Subsequently, the farmland whose area and thickness of the soil surface layer were 322 m^2 and 0.2 m, respectively, was reclaimed by employing human and animal labor. Sixteen constructability concepts (Table 2), which were chronologically established by the Construction Industry Institute into three phases: conceptual planning, design/procurement, and field operation, were applied to the farmland reclamation (Koda et al. 2020). Constructability criteria were generated from the constructability concepts for economic and efficient farmland reclamation.

(2) Farmland reclamation model

The farmland was reclaimed on a barren terrain located on the right bank and higher than the full water level of the Adizaboy micro-dam reservoir since they could utilize the farming route from the center of Agulae village to the right bank of the micro-dam reservoir. The construction period started in March and finished in May—at the end of the dry season, during the cultivation counter season. Subsequent to tree mowing, gravel and stones were removed from the planned site of the reclaimed farmland, and micro-dam reservoir sediments were excavated and transported by manpower and livestock to the site. After the removal of diverse sludges, leveling and site preparation were initiated. Girmay et al. (2012) conducted a cost-effective analysis of garlic cultivation, employing the sediments in the Maileba micro-dam reservoir in Tigray and demonstrated that the optimum thickness of the reclaimed farmland was 0.15 m. In this study, 0.05 m of sediments were added to

Table 2. Sixteen constructability concepts

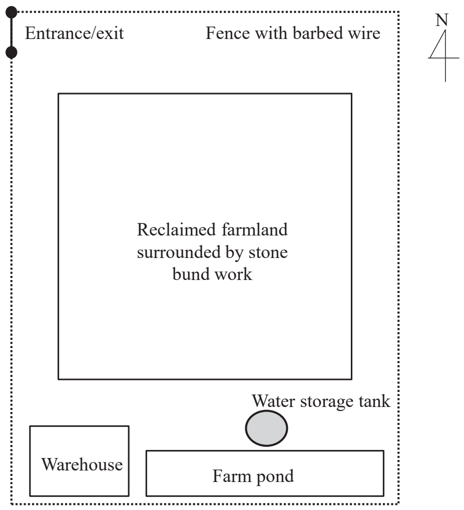
Conceptual planning phase
Concept 1-A: The constructability program should be made an integral part of the project execution plan.
Concept 1-B: Special emphasis should be placed on maintaining an effective project team.
Concept 1-C: Early project planning should actively involve individuals with current construction knowledge and experience.
Concept 1-D: This early construction involvement should be a consideration in developing the contracting strategy.
Concept 1-E: The master project schedule should be start-up and construction-sensitive.
Concept 1-F: Major construction methods should be analyzed in-depth early on and should be facilitated through proper facility design.
Concept 1-G: Site layouts should promote efficient construction, operation, and maintenance.
Design and procurement phase
Concept 2-A: Design and procurement schedules should be construction-driven.
Concept 2-B: The capabilities and benefits of advanced information technology should be exploited.
Concept 2-C: Designs should be configured to enable efficient construction.
Concept 2-D: Design elements should be standardized.
Concept 2-E: Technical specifications should promote construction efficiency.
Concept 2-F: Detailed designs of modules and preassemblies should be prepared to facilitate efficient fabrication, transport, and installation.
Concept 2-G: Project designs should promote accessibility to materials and equipment by construction personnel.
Concept 2-H: Designs should allow for and enable construction under adverse weather conditions.
Field operation phase
Concept 3-A: Special effort should be applied toward developing innovative construction methods.

compensate for the soil loss and to set the thickness of the soil surface layer of the reclaimed farmland to approximately 0.2 m in total, which was applicable for shallow-rooted garlic cultivation. The dredging volume of sediments was approximately 78 m^3, and the reclaimed farmland area was 322 m^2. The perspective challenge would be the augmentation of the reclaimed farmland because the reclaimable farmland area was evaluated as 3.2 ha, as previously mentioned at the end of Section 2.

(3) Vegetable cultivation and irrigation model

Figure 6 shows a pictographic view of the reclaimed farmland, including the irrigation system. A photograph taken from a high vantage point in front of a farm pond is incorporated in this figure. The reclaimed farmland is located at the back. To cultivate vegetables even during the dry season, a farm pond (water storage capacity: 85.4 m^3) was constructed to store water at a relatively higher place in the reclaimed farmland site. Excavated soil sediments from the farm pond construction were piled up to a height of approximately one meter, and water from the farm pond was manually transferred to a water storage tank installed on the banking part made by putting sediment. Drip irrigation was applied. The embankment was placed to the right of the water storage tank to prevent runoff from entering the reclaimed farmland during intensive rainfall. To reduce the evaporation of stored water in the farm pond, a thin cover with a eucalyptus tree framework was installed.

On the reclaimed farmland, we conducted the crop rotation of onion or garlic three times a year. The onion yield by using drip irrigation was 14.3 t/ha in 2019, which was greater than the average yield of 10.4 t/ha in Ethiopia. Nutrients, including potassium, were absorbed by the plants in the soil of the reclaimed farmlands. The onion yield was improved by the effective absorption of water by the plant roots, which might be induced by the water supply near the roots with drip irrigation.



Schematic representation of reclaimed farmland

Reclaimed farmland

Thin cover with eucalyptus tree framework

Fig. 6. Pictographic view of reclaimed farmland

Future prospect

In the Ethiopian highlands, soil erosion has been progressing due to felling and farming activities by the inhabitants. The maintenance and management of micro-dam reservoirs in the Tigray region are of urgent concern, and soil improvement technologies, such as additional soil application to existing farmland and farmland reclamation using micro-dam reservoir sediments, are expected to be effective solutions. As with farmland improvement projects implemented in Japan, it is essential to educate and foster local engineers and cooperate with local residents in promoting infrastructure related to sustainable agricultural production and developing degraded micro-dam reservoirs. Specifically, agricultural and rural engineering plays a role in managing local resources such as water and soil. For the sustainable utilization of water and soil, it is necessary to uphold conservational activities and establish a system to follow the principles and improve the awareness of the local residents toward conservation through training based on established technologies. Additionally, the water and soil management technology model is expected to contribute to various sustainable development goals, such as recovery from farmland degradation, building resilient infrastructure, promoting sustainable agriculture, and eradicating poverty and hunger.

The Aglae village office will manage the farmland to create new farming opportunities for a group of young landless farmers etc. to support their rural life and farming activities. By growing two to three vegetable crops a year, such as onion and garlic, which are in high demand and have low height and shallow roots, farmers can expect to improve their standard of living.

To promote sustainable agriculture and maximize yield, the following factors must take place: the training of farmers, which will be mainly conducted by Mekelle University; implementation of smart agriculture technologies and maintenance and strengthening of organizational management systems. If they can apply for the remote monitoring of soil moisture, farmers can go to the reclaimed farmland for irrigation when the soil moisture is low. They can also pump-up water stored in the farm pond to the water tank if they can make use of solar energy. Consequently, it is expected that technologies that contribute to the sustainable use of micro-dam reservoirs and increase food production will be implemented in micro-dam reservoirs outside Tigray to benefit the next generation.

Acknowledgements

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