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Diagnostic Assessment in the Wet and Dry Seasons of Simple Weirs Constructed by Small-Scale Farmers in the Northern Region Provinces of Zambia

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Abstract: An intervention recently made in Zambia is the promotion of small-scale irrigation using simple weirs, which aims to encourage small-scale farmers in the country's rural areas to engage in irrigated food production throughout the dry season. This irrigation method relies on conventional weirs to divert the river's flow. This study was carried out in three northern region provinces of Zambia between November 2022 and January 2023 to conduct a functional diagnostic assessment of simple weirs during the dry and rainy seasons. In this study, 15 simple weirs were chosen for investigation. The goal of this study was to determine their physical status, identify their problems and scope, and evaluate simple weirs' potential for river water diversion. According to this study, 26% of the weirs had broken sections and 67% were in excellent condition (being recently maintained and restored). Despite the challenges mentioned earlier, farmers have continued to construct them because they cannot afford to purchase stone or concrete irrigation structures due to the location and/or small-scale area available for irrigation development. Simple weirs may act as a beneficial supplement to irrigation technologies. The use of local building materials and the use of traditional skills is encouraged by this technology.

Keywords: simple weirs; small-scale irrigation; rural areas; upstream water level; emerging farmers; dryland

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1. Introduction

According to estimates, up to 70% of the population in sub-Saharan Africa is composed of low-income individuals who live in rural areas and rely heavily on rainfed agriculture to earn their living. This population's reliance on the rainy season for agriculture does present several potential challenges, including unreliable weather patterns, a shorter rainy season, and an increase in agricultural pests [1]. According to estimates, small-scale farmers in rural areas of Zambia, wherein 74–80% of the population lives, rely on rainfed agriculture for their livelihood [2]. Agriculture is a major source of food and income in many rural parts of Zambia, with small-scale farmers producing the majority of the country's food. In Zambia's rural areas, the majority of small-scale farmers rely on the yearly crops collected in June and July for both food and money. However, most family food stores in rural areas begin to diminish in October. The majority of rural households experience severe food shortages between January and April. In order to survive food shortages during this season and prepare for the following harvest, the majority of rural households skip meals.

Despite small-scale irrigation producing relatively high returns, previous research has shown that expanding small-scale irrigation is typically difficult due to biophysical considerations [3]. Zambia's rural areas struggle with a lack of appropriate low-cost irrigation methods, much like other small-scale irrigation systems in sub-Saharan Africa. Small-scale farmers in rural areas are solely dependent on crude irrigation techniques, which means there are restrictions on how far irrigation activities can be expanded. In Sub-Saharan Africa, irrigation schemes of all sizes have transitioned from government support to self-help. It is for this reason that small-scale farmers will inevitably embrace innovative irrigation techniques as the demand for year-round food production rises, and they may diversify their sources of income through small-scale dry season irrigation [4]. Finding substitute affordable irrigation techniques is crucial for improving the rural livelihoods of the vast majority of Africans. When compared to pressurised irrigation systems, some small-scale irrigation techniques have been reported to yield comparatively large returns per unit.

Off-season small-scale irrigation in arid and semi-arid areas of sub-Saharan Africa can be optimised by using simple structures, technologies, and practices that allow river water to be diverted for off-season small-scale irrigation of high-value crops [5–7]. In order to improve rural people's nutrition and food security, small-scale irrigation development has been incorporated into agricultural strategies in several African nations. After the implementation of strategies for creating and promoting other types of irrigation, small-scale irrigation areas have shown growth in comparison to medium- or large-scale irrigation areas [8–10]. Studies have determined that there are up to 20.5 million hectares of irrigable land in sub-Saharan Africa that might be used for river diversion, of which 3 million are in southern Africa [11]. Because of this potential, small-scale irrigation is anticipated to be extremely important in rural parts of sub-Saharan Africa wherein there is a need to lessen poverty and improve food security for the vast majority of impoverished people.

However, most of the small-scale farmers in sub-Saharan Africa manually draw water for dry season irrigation from shallow wells, rivers, and streams using buckets, watering cans, treadle pumps, and plastic containers. This type of irrigation practice is common in remote rural areas in most developing countries. In Zambia, about 80% of the total number of small-scale farmers in rural areas of Zambia use watering cans, buckets, and scooping techniques to irrigate crops [12–14].

However, most small-scale rural farmers in Zambia are moving away from these old-fashioned manual irrigation techniques and towards less labour-intensive inventions such as simple weirs [15]. A simple weir is a temporary hydraulic structure with a low head that is built across a river channel to redirect river water. These structures are comparatively inexpensive, suitable for rural settings, and have the capacity for gravity irrigation [16]. The water provided by these types of irrigation structures is utilised for a variety of reasons in the northern region, including irrigation of crops during the dry season, supplemental irrigation during dry spells, and water supply for inland fish farming and research [17]. In the provinces of Luapula, Copperbelt, and North-Western, wherein the dry season lasts from May to December, these kinds of irrigation structures are built frequently and for every dry season [18].

In locations with rivers, springs, and streams, simple weirs in addition to concrete-constructed irrigation structures play a crucial role in irrigation to improve household food security in many nations and regions where irrigation technology has not yet been adopted. To help small-scale farmers in distant areas of developing countries, several researchers have studied affordable low-cost irrigation technologies. Most of them have been recommended for implementation and adoption by small-scale farmers. The purpose of this study was to determine whether these structures constructed by farmers themselves would sustain for one dry season. The usefulness of simple weirs has been the subject of numerous reports, but none have examined their longevity yet. The findings of this study will be valuable for researchers and engineers interested in the parameters affecting the durability of these structures.

In Zambia, Malawi, and Mozambique, among other countries in sub-Saharan Africa, these structures and the recent addition of simple weirs are becoming more commonly recognised in the development and promotion of community-based irrigation systems [19]. Since the introduction of simple weirs, they have helped to promote and develop small-scale irrigation, enabled emerging farmers to switch from traditional irrigation methods to better irrigation practices, and helped new farmers gain experience in the management and operation of community-based small-scale irrigation schemes [20].

Due to a lack of research and experimental findings on these types of weirs, their design and the material selection methods, there is a strong need to identify structural constraints and challenges faced by farmers. In order to comprehend the technical viability of this traditional technology, this study carried out a functional diagnostic assessment, concentrating on (i) the difficulties and drawbacks of single-line weirs and (ii) the water diversion volume potentially available for irrigation. Therefore, the goal of this study was to evaluate single-line weirs built by farmers in the aforementioned region.

2. Methodology

2.1. Study Areas

This study was carried out in the northern part of Zambia, which includes the provinces of Luapula, Copperbelt, and North-Western, as shown in Figure 1 [21,22].

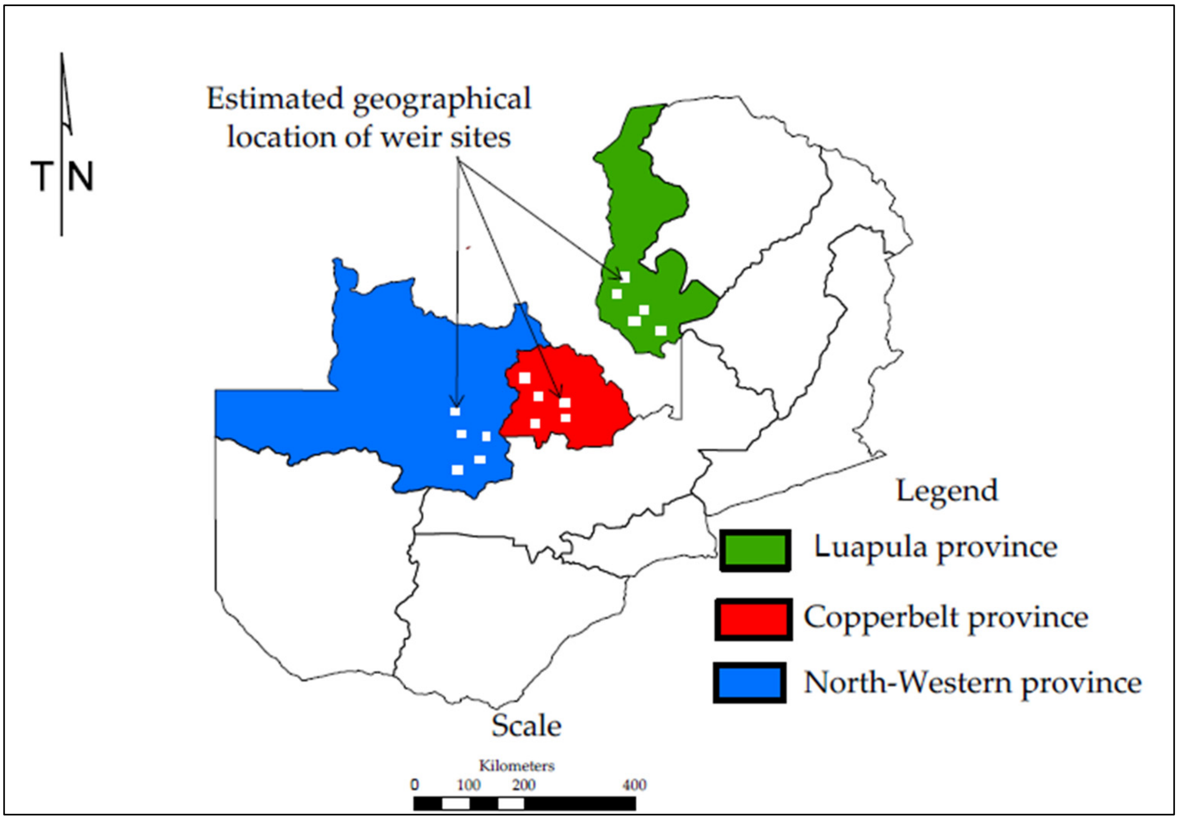

Figure 1. Geographical location of the study area and estimated location of the sites for simple weirs.

2.2. Rainfall

Zambia has two distinct seasons. The rainy season begins in late October and lasts until late April. Effective rains, however, occur from late December to early April [23]. The dry season, which lasts from early May to late November, comes after the wet season, as shown in Figure 2. Variations in (i) altitude, (ii) latitude, (iii) temperature, (iv) humidity, and (v) wind movements are what define Zambia's rainfall pattern.

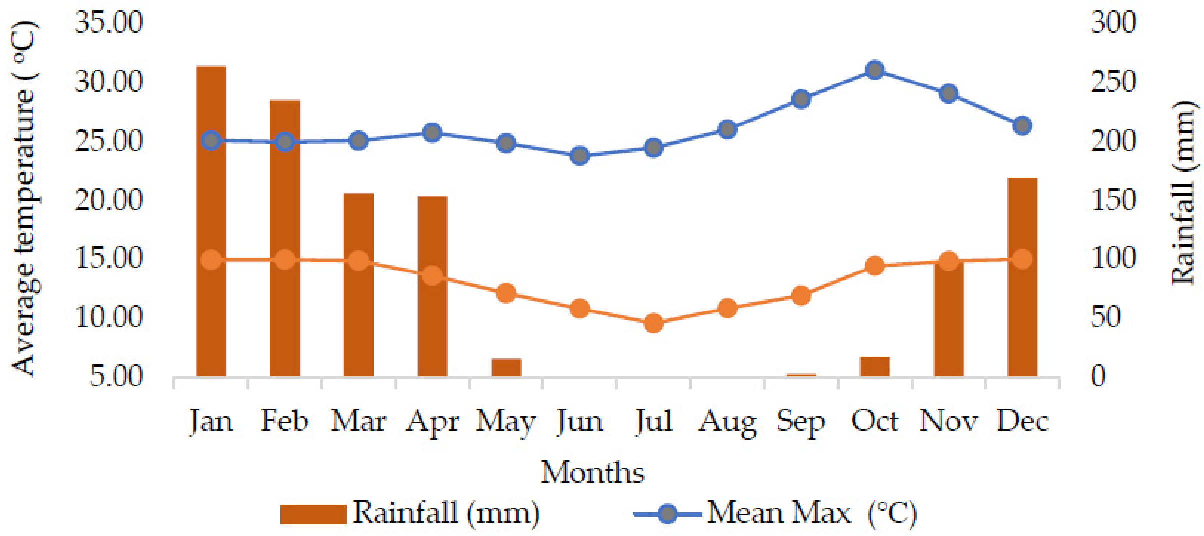

Figure 2. Annual rainfall distribution pattern.

Three agroecological zones categorise the annual rainfall in Zambia. The zones are classified as Zone I, with an annual precipitation level of less than 750 mm; Zone II, with an annual precipitation level between 900 mm and 1200 mm; and Zone III, with an annual precipitation level of more than 1400 mm [24,25]. With an annual rainfall of 1000–1500 mm and a growth season of 120–150 days, it covers 41% of the country, including parts of the Central African Plateau in the Northern, Luapula, Copperbelt, and North-Western provinces, as well as parts of the Serenje and Mkushi districts. Due to soil conditions, only 53% of the land is fit for cultivation. This, together with limited market access, limits the number of crop types that can be grown. There are several wetlands, dambos, rivers, and lakes, but poor commercialisation limits irrigated output.

In Zambia, rivers, lakes, and groundwater make up around 40% of the nation's total water supply. Zambia's northern provinces are blessed with perennial rivers. The region has two major river basins, the Tanganyika River basin and the Chambeshi River basin [26,27]. The Chambeshi and Luapula rivers are the two main rivers in Zambia's northern area, both of which are part of the Congo River basin. Lake Mweru, Mweru Wantipa, Bangweulu, and Tanganyika are the principal surface water bodies of the Chambeshi/Luapula river network. Zambia has tremendous water resources but has done little to utilize them through irrigation system investments, and many farmers continue to rely on rainfed cropping cycles. The Zambian smallholder farming community is very vulnerable to the effects of global warming and climate change. This state of affairs creates significant challenges in attaining water security, maintaining crop productivity, supporting economic growth, and enhancing livelihoods. Rainfed subsistence agriculture, which is widely practised in Zambia, is under threat from fluctuating rainfall patterns and has failed to significantly enhance crop production or smooth out cycles of hunger and food insecurity.

2.3. Research Framework

Due to availability and accessibility limitations, the study area was divided into three provinces, with five sites of equal proportion selected randomly from each province, as illustrated in Figure 3. For the current investigation, in all, 15 structures were chosen based on geographical location [28,29]. Furthermore, monitoring field inspections were carried out three times on each weir. Simple weir structures constructed along the same river were treated in this study as a single diversion. It was regarded in this way to avoid data duplication.

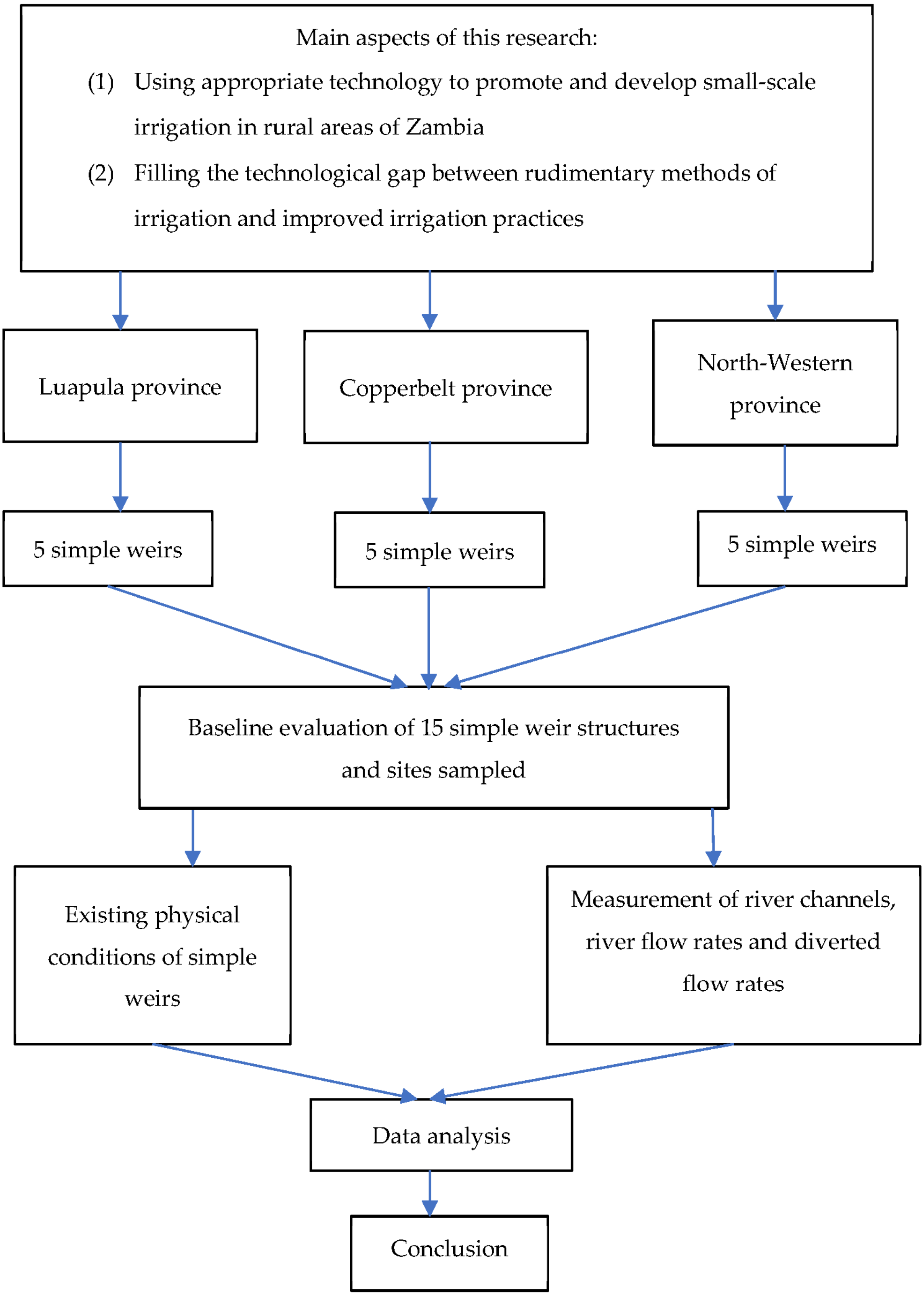

Figure 3. Schematic research framework.

2.4. River Profile Data

At each site, river width and average depths were measured to establish the geometry and to calculate the cross-sectional area of the river. The obtained cross-sectional area was then multiplied by the estimated river velocity using the floating method.

2.5. Discharge Measuring Procedure Using the Floating Method

2.5.1. Calculation of the Cross-Sectional Area of the River

The following equations were used to compute the volumetric river flow rates and the volume of water diverted at each weir's intake structure: (1), (2), (3), and (4). The first step was to measure the river's width (W). The next step was to measure the depth of the river at equidistance-spaced points across the river's width. The average depth (D) of the river was calculated. The following formula was used to obtain the cross-sectional area of each river [30].

$$A = D \times W \tag{1}$$

where A is the cross-sectional area (m^2), w is the river width (m), and D is the average river depth (m).

2.5.2. Measuring River Velocity Using the Floating Method

Items needed for this exercise were: a timer, floater, measuring tape, and two marking-out pegs. Two pegs were placed 1–5 m apart upstream and downstream along the riverbank. The floater was thrown into the river, where it was barely submerged at upstream and carried downstream by water until it reached the downstream peg; this movement was timed with a stopwatch. Three iterations were completed to determine the average velocity (V).

The theoretical river discharge (Q) was calculated by multiplying the river's cross-sectional area by the estimated water velocity:

$$Q = V \times A \tag{2}$$

where Q is the mathematical volumetric discharge (m^3/s), V is the average velocity of water in the river channel (m/s), and A is the cross-sectional area (m^2).

In order to account for the natural changes in flow rates, in Equation (2), the quantitative estimation of the water flow rate is multiplied by 0.8.

$$Qa = Q \times 0.8 \tag{3}$$

We then obtained the flow rate diversion coefficient (Cd), which is defined as

$$Cd = \frac{\text{River Flow rate diverte}}{\text{River Flow rate}} \tag{4}$$

In this study, the diversion coefficient is calculated as the percentage of the river flow that is diverted at the water intake [31].

2.6. Questionaire Format for Raw Data Collection

Key informants from different stakeholders were interviewed. The questionnaire format in Table 1 was used to interview a total of 89 persons: Luapula (participants, n = 39), Copperbelt (participants, n = 27), and North-Western (participants, n = 23). This was conducted through discussions with members of the simple weir irrigation scheme, interviews with local agricultural extension officers, and site visits. Since most of the problems aired during participant talks were echoes of earlier issues, the sample size and number of people interviewed were determined to be sufficient for this study.

Table 1. The questionnaire for functional diagnosis of simple weirs.

Month	Reporting Date							
Name of Province	Name of District		Name of Simple Weir site					
Climatic Information								
Annual rainfall (mm)								
Main source of water	Perennial river		Seasonal stream		Spring			
Irrigation method								
Irrigable command area (ha)								
Main crops								
Type of simple weir	Single-line		Double-line		Trigonal		Inclined	
Width of simple weir (m)								
Riverbed foundation characteristics	Rocky foundation		Sandy		Gravel			
Highest river discharge (m^3/s)								
Lowest river discharge (m^3/s)								
Water intake slope (%)								
Average amount of water diverted for irrigation (from May to October)								
Source of construction material								
Type of construction materials								
Type of labour								

3. Results

3.1. Types of Simple Weirs Constructed by Farmers

The key materials used in the construction of these types of structures are forest poles, thatch grass, and tree bark. In many instances, these kinds of materials are readily available in the local forest. Simple weirs are constructed using local forest material because most of the rivers in the region have foundations that are too weak to support masonry or concrete structures. Simple weirs may be categorised in four ways: single-line weirs, double-line weirs, inclined weirs, and trigonal weirs [32]. In this study, our discussions focused on the single-line simple weirs because they are the form most preferred by the farmers in the region. This is shown by the high proportion of single-line simple weirs in Figure 4. These types of structures are suitable for perennial rivers and streams with constant flowing water. Other considerations for these structures include the future upgrading of the structure into a permanent facility, the use of local skills, structural simplicity, and river flow regimes during the dry season [33].

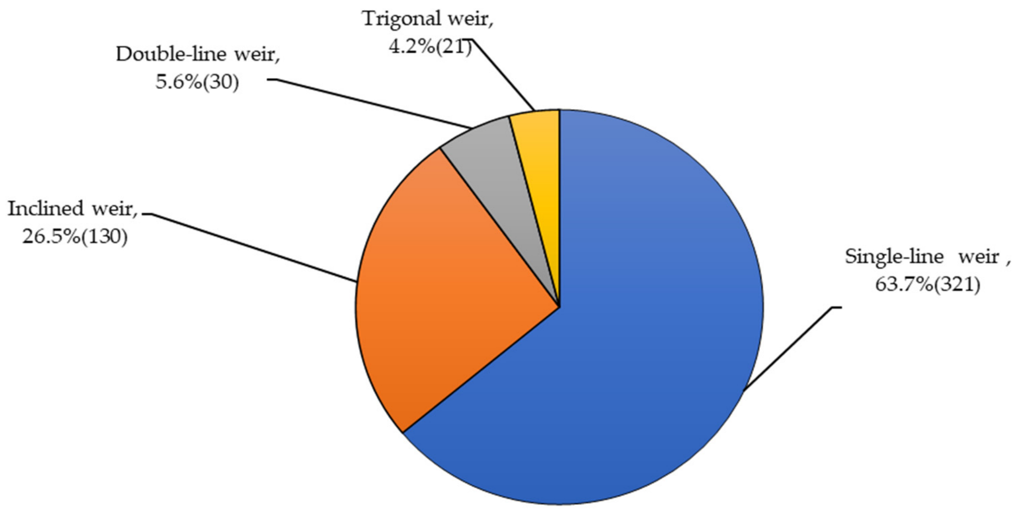

Figure 4. Base-line data on the proportion of four types of simple weirs, 2022 survey.

As previously said, basic weirs are essentially constructed as water intake weirs over the river's width. These structures have previously been established and promoted as best practice for small-scale irrigation development in Zambia's Luapula, Copperbelt, and North-Western regions. However, information regarding the design, use, and maintenance of these structures is currently lacking. One of the concerns raised in this paper is the issue regarding maintenance. The study discovered a considerable variation in the amount of water diverted by regularly and irregularly maintained weirs. It is for this reason that many studies have stressed the importance of irrigation structure maintenance [34,35].

3.2. Prevailing Physical Condition Based on Rating Criteria

The findings in Figure 5 indicate the actual physical circumstances at the time of the field visit. The four Luapula weirs, three Copperbelt weirs, and three North-Western weirs made up 67% (10) of the single-line weirs that were in excellent condition (newly constructed, maintained, or restored).

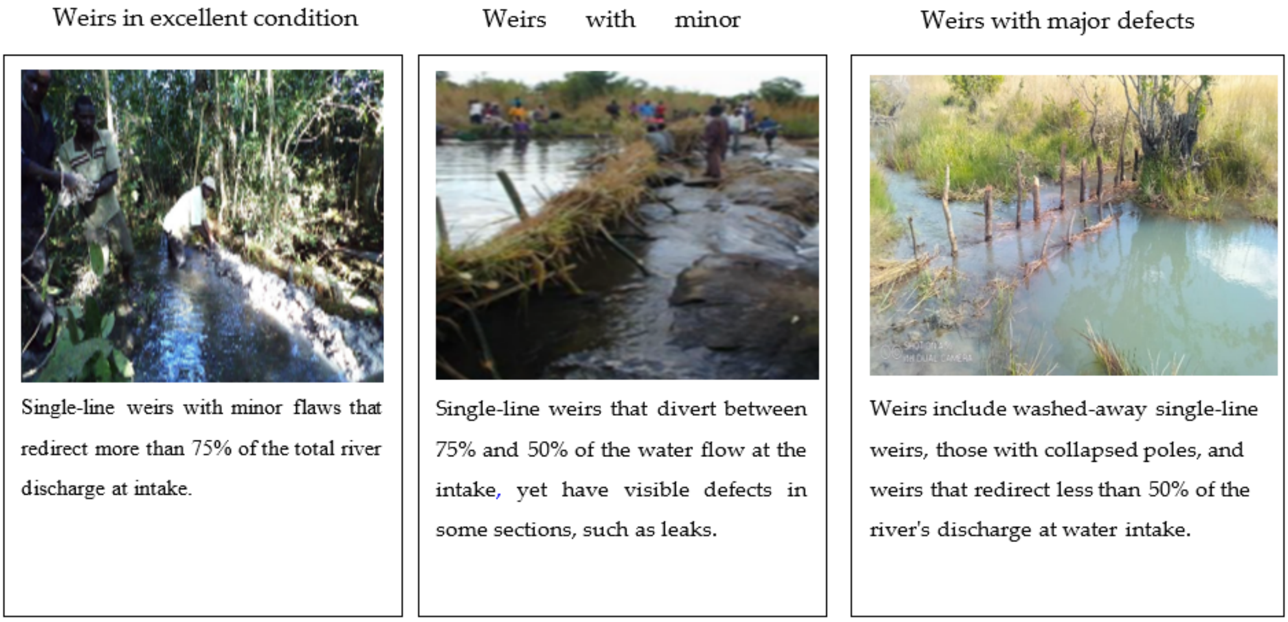

Figure 5. Photographs of the existing simple weirs. Simple weirs were rated based on the state of their structures and the amount of flow diverted.

Weirs in Luapula province, the Copperbelt province, and the North-Western province all had partial damage, totalling 26% (four weirs), in the form of leaking, loose connections, and decomposing thatch grass. The study also found that the wet season (November to March) was the time during which single-line weirs were most susceptible to destruction. While 7% (one weir) of sites in the Copperbelt were found to have a washed-away weir, this was probably due to the increase in river inflow. The study also showed that single-line weirs were particularly susceptible to damage during the wet season (November to March). Because single-line weirs are prone to flood damage, they have difficulties that necessitate yearly or even more frequent reconstruction. However, it was also discovered by the study that 33% (5/15) of the single-line weirs had suffered damage during the dry season, as detailed in Table 2.

Table 2. Physical condition of the existing weir samples (survey from November 2022).

Province	Excellent Condition	Partially Damaged	Flushed-Off Weirs
Luapula	4	1	0
Copperbelt	3	1	1
North-Western	3	2	0

3.3. The Inherent Characteristics of River Geometric Structures in Luapula, Copperbelt, and North-Western Provinces

Tables 3–5 contain data summaries for the rivers that single-line weirs diverted. These include dimensional and volumetric discharge characteristics across 15 single-line weirs, measured between 12 November and 30 December 2022. According to the study, river width and depth affect how much river water the single-line weir can divert.

Table 3. Data profile for each site in Luapula province.

Profile Parameters	L1	L2	L3	L4	L5
Observation time (s)	55.70	56.00	66.00	58.30	62.30
Length of river section (m)	2.00	2.40	1.50	1.80	2.00
Average river velocity (m/s)	0.04	0.04	0.02	0.03	0.03
River width (m)	2.90	2.67	5.73	7.30	5.23
River depth (m)	0.98	1.50	1.50	1.20	1.40
Cross-sectional area (m^2)	2.84	4.00	8.60	8.76	7.32
River discharge (m^3/s)	0.10	0.17	0.20	0.27	0.23
Single-line weir height (m)	1.00	1.60	1.50	1.30	1.50
Single-line weir length (m)	3.00	2.50	6.00	7.20	5.00

Table 4. Data profile for each site in Copperbelt province.

Profile Parameters	C1	C2	C3	C4	C5
Observation time (s)	41.80	60.00	63.70	60.00	61.67
Length of river section (m)	1.20	1.40	1.50	1.60	1.40
Average river velocity (m/s)	0.03	0.02	0.02	0.03	0.02
River width (m)	6.30	9.10	7.40	5.50	6.70
River depth (m)	1.30	1.30	1.10	1.56	1.10
Cross-sectional area (m^2)	8.19	11.83	8.14	8.58	7.37
River discharge (m^3/s)	0.23	0.28	0.19	0.23	0.17
Single-line weir height (m)	1.00	1.50	0.90	1.30	1.20
Single-line weir length (m)	6.50	10.00	7.50	6.00	7.00

Table 5. Data profile for each site in North-Western province.

Profile Parameters	NW1	NW2	NW3	NW4	NW5
Observation time (s)	57.30	60.00	61.67	56.67	61.67
Length of river section (m)	2.20	2.00	2.50	1.20	1.60
Average river velocity (m/s)	0.04	0.03	0.04	0.02	0.03
River width (m)	4.90	5.70	7.10	6.30	6.00
River depth (m)	1.30	1.50	1.10	1.30	1.40
Cross-sectional area (m^2)	6.37	8.55	7.81	8.19	8.40
River discharge (m^3/s)	0.24	0.29	0.32	0.17	0.22
Single-line weir height (m)	1.20	1.40	1.00	1.50	1.30
Single-line weir length (m)	5.00	6.00	7.00	6.50	6.00

In Luapula province, river widths ranged from 2.9 to 7.3 m, river depths ranged from 0.98 to 1.4 m, and river flows ranged from 0.1 to 0.27 m per second. In Copperbelt province, river widths ranged from 5.5 to 9.1 m, river depths ranged from 1.1 to 1.6 m, and river flows ranged from 0.17 to 0.28 m per second. In the North-Western province, river discharges ranged from 0.17 to 0.32 m^3/s, depths ranged from 1.1 to 1.5 m, and widths ranged from 4.9 to 7.1 m. The results of this analysis show the maximum flood level and the amount of flow divergence that could be produced via the installation of single-line weirs.

3.3.1. Geometric Profiles for rivers in Luapula Province

The profiles of the five rivers assessed in Luapila province are presented in Tables 5–9 and Figures 6–10.

Table 6. Summary of measurements, calculation of inflows, and amount of diversion at site L1.

Date	Average Depth (D) (m)	River Width (m)	Cross-Sectional Area (m^2)	Average Water Velocity (V) (m/s)	Calculated Discharge (Q) (m^3/s)	Actual River Discharge (Multiplied by a Factor of 0.8)
12–15 November 2022	0.40	3.48	1.40	0.04	0.06	0.04

Table 7. Summary of measurements, calculation of inflows, and amount of diversion at site L2.

Date	Average Depth (D) (m)	River Width (m)	Cross-Sectional Area (m^2)	Average Water Velocity (V) (m/s)	Calculated Discharge (Q) (m^3/s)	Actual River Discharge (Multiplied by a Factor of 0.8)
16–19 November 2022	0.30	2.60	0.78	0.02	0.02	0.01

Table 8. Summary of measurements, calculation of inflows, and amount of diversion at site L3.

Date	Average Depth (D) (m)	River Width (m)	Cross-Sectional Area (m^2)	Average Water Velocity (V) (m/s)	Calculated Discharge (Q) (m^3/s)	Actual River Discharge (Multiplied by a Factor of 0.8)
20–23 November 2022	0.70	5.70	3.99	0.03	0.12	0.10

Table 9. Summary of measurements, calculation of inflows, and amount of diversion at site L4.

Date	Average Depth (D) (m)	River Width (m)	Cross-Sectional Area (m^2)	Average Water Velocity (V) (m/s)	Calculated Discharge (Q) (m^3/s)	Actual River Discharge (Multiplied by a Factor of 0.8)
24–27 November 2022	0.40	7.30	2.92	0.03	0.09	0.07

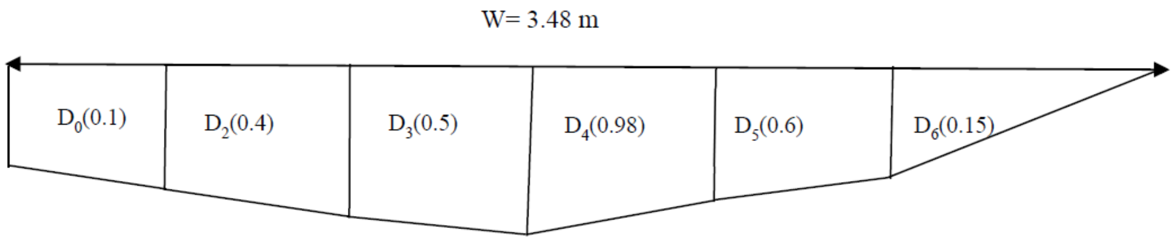

Figure 6. Geometric details of the river at site L1.

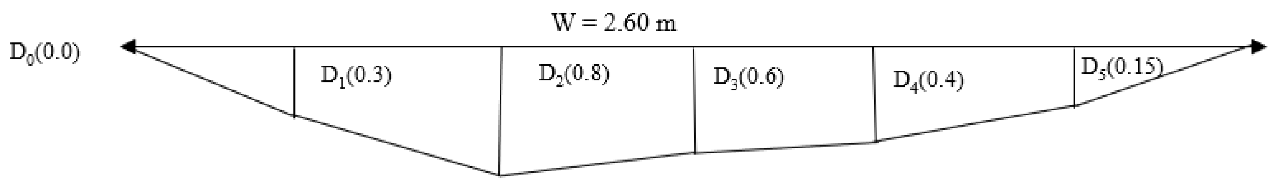

Figure 7. Geometric details of the river at site L2.

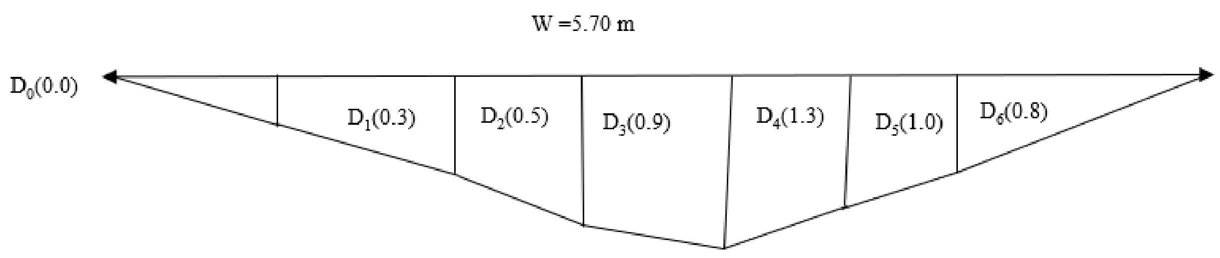

Figure 8. Geometric details of the river at site L3.

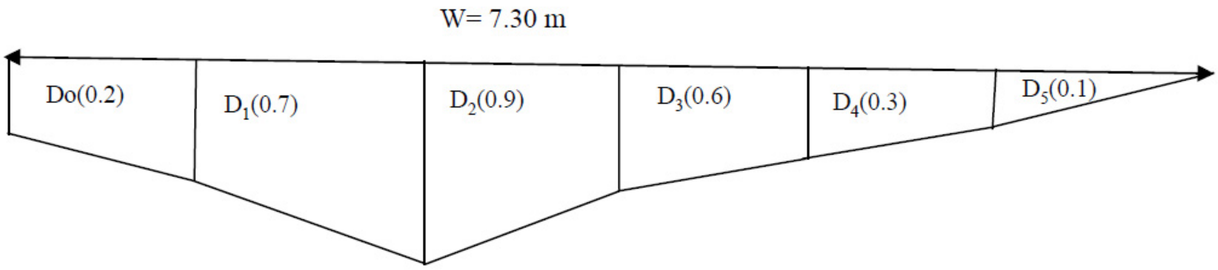

Figure 9. Geometric details of the river at site L4.

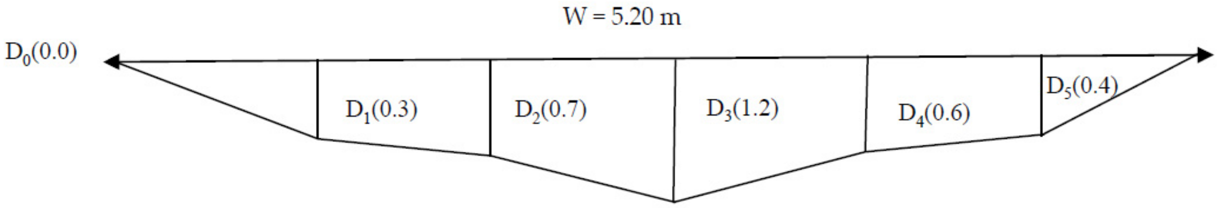

Figure 10. Geometric details of the river at site L5.

3.3.2. Geometric profiles for rivers in Copperbelt province

The profiles of the five rivers targeted in Copperbelt province are presented in Tables 10–14 and Figures 11–15.

Table 10. Summary of measurements, calculation of inflows, and amount of diversion at site L5.

Date	Average Depth (D) (m)	River Width (m)	Cross-Sectional Area (m^2)	Average Water Velocity (V) (m/s)	Calculated Discharge (Q) (m^3/s)	Actual River Discharge (Multiplied by a Factor of 0.8)
28–30 November 2022	0.50	5.20	2.60	0.03	0.08	0.06

Table 11. Summary of measurements, calculation of inflows, and amount of diversion at site C1.

Date	Average Depth (D) (m)	River Width (m)	Cross-Sectional Area (m^2)	Average Water Velocity (V) (m/s)	Calculated Discharge (Q) (m^3/s)	Actual River Discharge (Multiplied by a Factor of 0.8)
3–4 December 2022	0.40	6.30	2.52	0.03	0.08	0.06

Table 12. Summary of measurements, calculation of inflows, and amount of diversion at site C2.

Date	Average Depth (D) (m)	River Width (m)	Cross-Sectional Area (m^2)	Average Water Velocity (V) (m/s)	Calculated Discharge (Q) (m^3/s)	Actual River Discharge (Multiplied by a Factor of 0.8)
5–6 December 2022	0.40	9.10	3.64	0.02	0.07	0.06

Table 13. Summary of measurements, calculation of inflows, and amount of diversion at site C3.

Date	Average Depth (D) (m)	River Width (m)	Cross-Sectional Area (m^2)	Average Water Velocity (V) (m/s)	Calculated Discharge (Q) (m^3/s)	Actual River Discharge (Multiplied by a Factor of 0.8)
7–8 December 2022	0.30	7.40	2.22	0.02	0.04	0.04

Table 14. Summary of measurements, calculation of inflows, and amount of diversion at site C4.

Date	Average Depth (D) (m)	River Width (m)	Cross-Sectional Area (m^2)	Average Water Velocity (V) (m/s)	Calculated Discharge (Q) (m^3/s)	Actual River Discharge (Multiplied by a Factor of 0.8)
8–9 December 2022	0.40	5.50	2.20	0.03	0.07	0.05

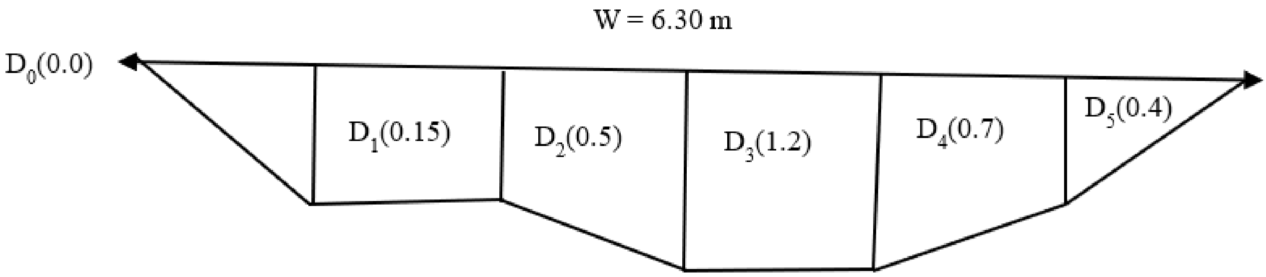

Figure 11. Geometric details of the river at site C1.

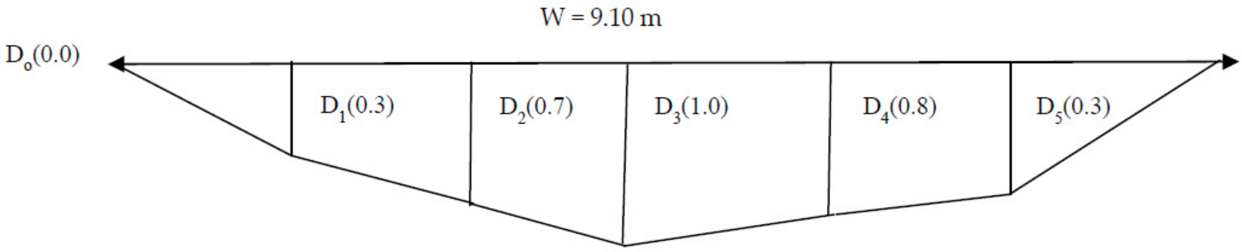

Figure 12. Geometric details of the river at site C2.

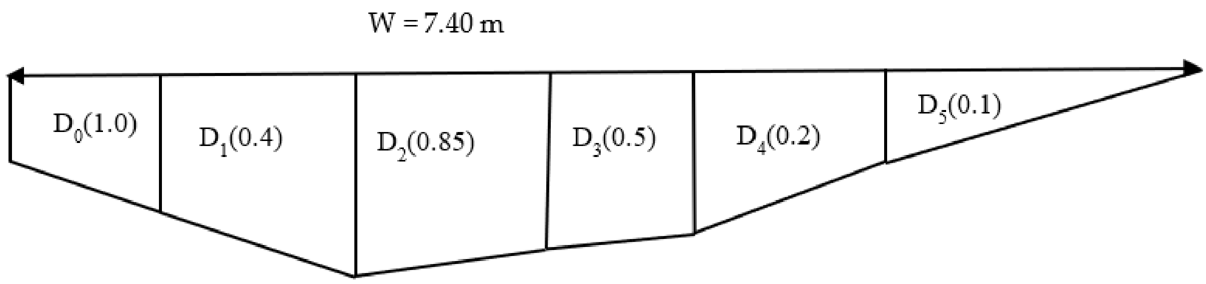

Figure 13. Geometric details of the river at site C3.

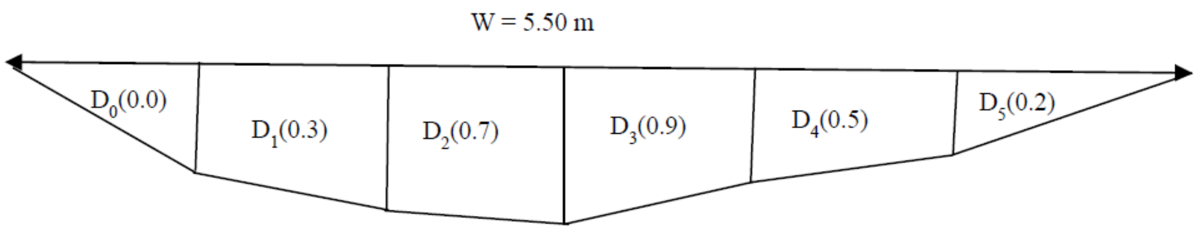

Figure 14. Geometric details of the river at the single-line weir site C4.

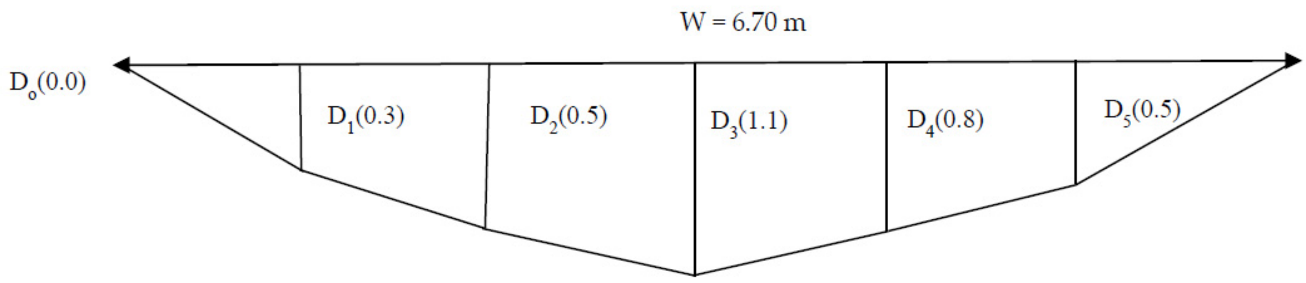

Figure 15. Geometric details of the river at the single-line weir site C5.

3.3.3. Geometric Profiles for Rivers in North-Western Province

The profiles of the five rivers targeted in North-Western province are presented in Tables 15–20 and Figures 16–20.

Table 15. Summary of measurements, calculation of inflows, and amount of diversion at site C5.

Date	Average Depth (D) (m)	River Width (m)	Cross-Sectional Area (m^2)	Average Water Velocity (V) (m/s)	Calculated Discharge (Q) (m^3/s)	Actual River Discharge (Multiplied by a Factor of 0.8)
13-14 December 2022	0.50	6.70	3.35	0.02	0.07	0.05

Table 16. Summary of measurements, calculation of inflows, and amount of diversion at site NW1.

Date	Average Depth (D) (m)	River Width (m)	Cross-Sectional Area (m^2)	Average Water Velocity (V) (m/s)	Calculated Discharge (Q) (m^3/s)	Actual River Discharge (Multiplied by a Factor of 0.8)
15–12 December 2022	0.40	4.90	1.96	0.04	0.07	0.06

Table 17. Summary of measurements, calculation of inflows, and amount of diversion at site NW2.

Date	Average Depth (D) (m)	River Width (m)	Cross-Sectional Area (m^2)	Average Water Velocity (V) (m/s)	Calculated Discharge (Q) (m^3/s)	Actual River Discharge (Multiplied by a Factor of 0.8)
18–20 December 2022	0.40	5.70	2.28	0.03	0.07	0.05

Table 18. Summary of measurements, calculation of inflows, and amount of diversion at site NW3.

Date	Average Depth (D) (m)	River Width (m)	Cross-Sectional Area (m^2)	Average Water Velocity (V) (m/s)	Calculated Discharge (Q) (m^3/s)	Actual River Discharge (Multiplied by a Factor of 0.8)
21–22 December 2022	0.40	7.50	3.00	0.04	0.12	0.10

Table 19. Summary of measurements, calculation of inflows, and amount of diversion at site NW4.

Date	Average Depth (D) (m)	River Width (m)	Cross-Sectional Area (m^2)	Average Water Velocity (V) (m/s)	Calculated Discharge (Q) (m^3/s)	Actual River Discharge (Multiplied by a Factor of 0.8)
23–26 December 2022	0.30	6.30	1.89	0.02	0.04	0.03

Table 20. Summary of measurements, calculation of inflows, and amount of diversion at site NW5.

Date	Average Depth (D) (m)	River Width (m)	Cross-Sectional Area (m^2)	Average Water Velocity (V) (m/s)	Calculated Discharge (Q) (m^3/s)	Actual River Discharge (Multiplied by a Factor of 0.8)
27–30 December 2022	0.20	6.00	1.20	0.03	0.04	0.03

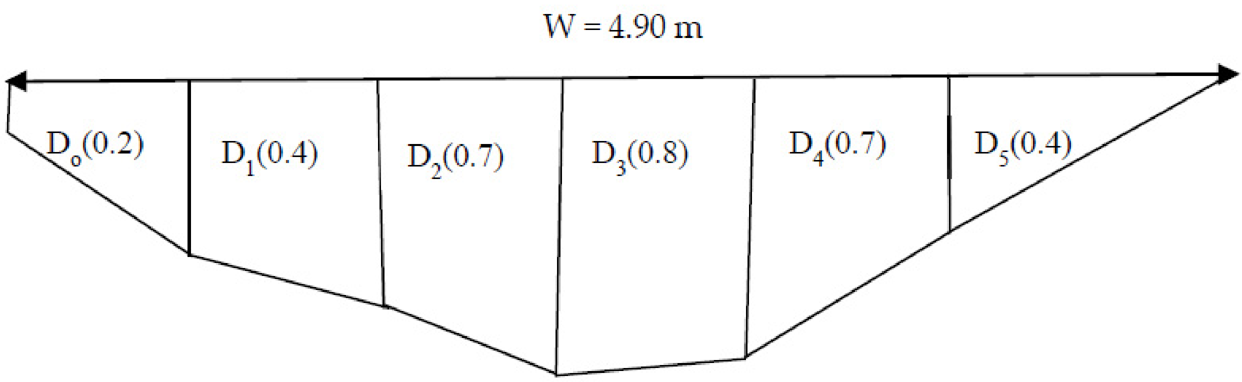

Figure 16. Geometric details of the river at the single-line weir site NW1.

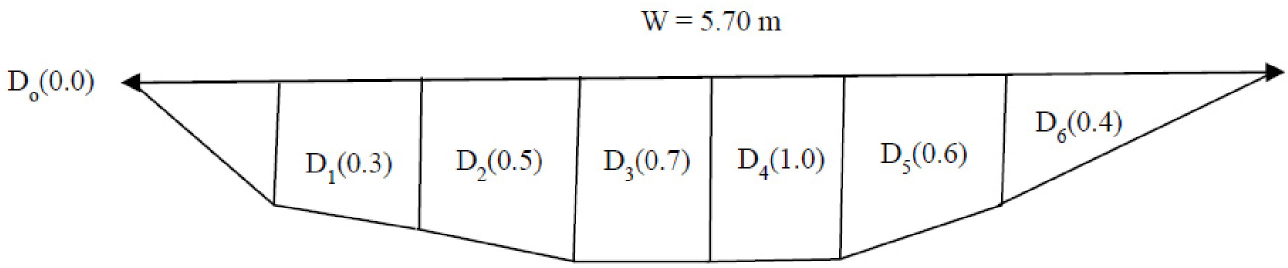

Figure 17. Geometric details of the river at the single-line weir site NW2.

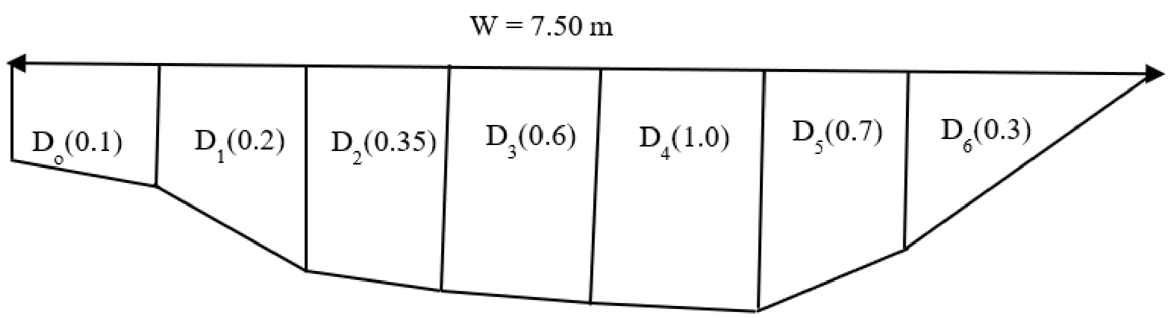

Figure 18. Geometric details of the river at the single-line weir site NW3.

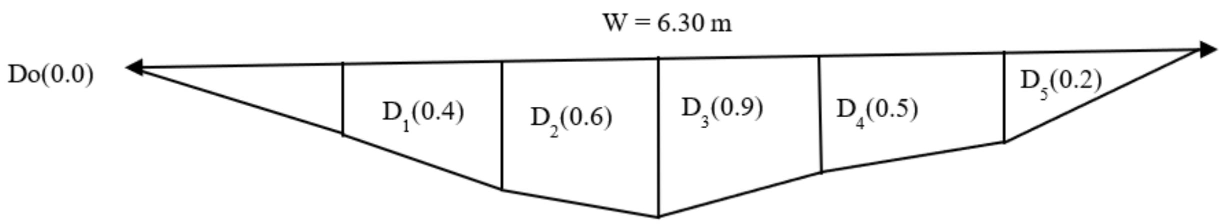

Figure 19. Geometric details of the river at the single-line weir site NW4.

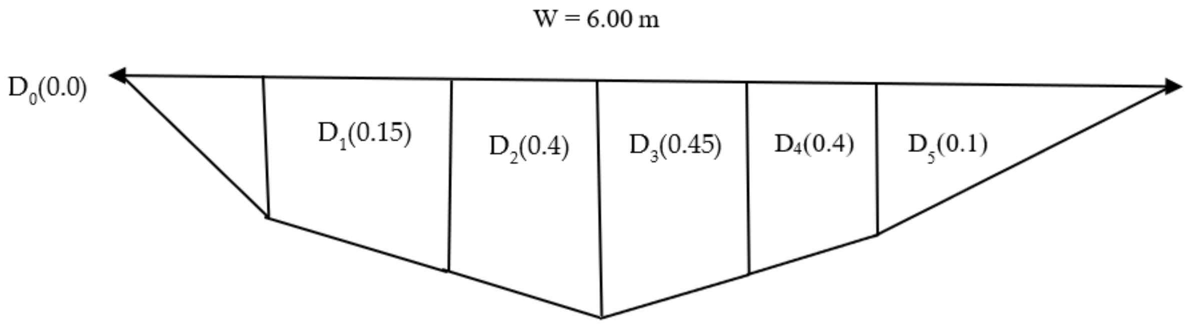

Figure 20. Geometric details of the river at the single-line weir site NW5.

3.4. River Inflow and Amount of Water Diversion

The study evaluated water diversion volumes at individual locations within each province. The water diversion volume results were compared. This analysis was necessary to determine the locations with the greatest magnitude of water diversion volumes. The least water diversion volume was recorded at L5, with 49% of the total river inflow. At L1, the water diversion volume was 90% of the total river inflow, whereas at L2, the water diversion volume was 70% of the total river inflow, and at L3 the water diversion volume was 92% as shown in Figure 21. This level of water diversion was attributed to regular maintenance of the weirs.

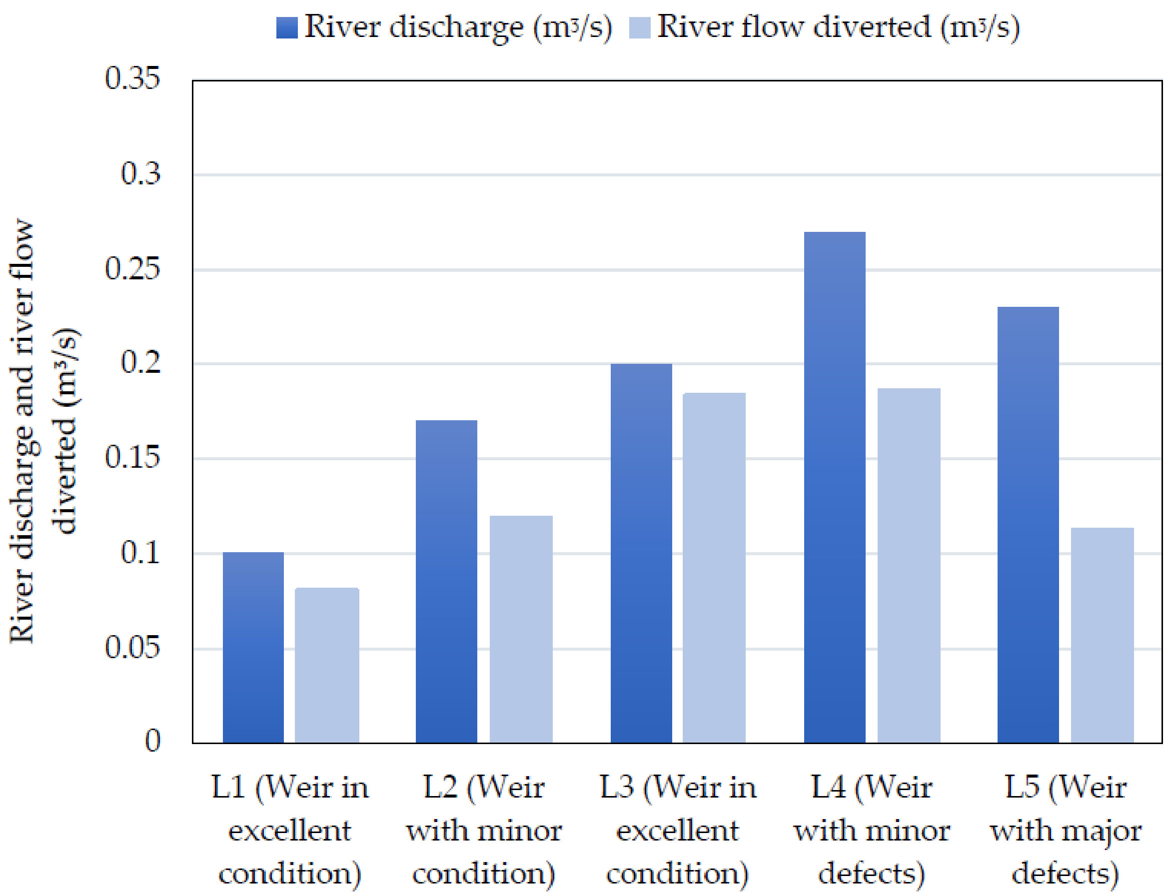

Figure 21. Weir condition, average river inflow, and water diversion volume.

According to the data collected from Copperbelt, the analysis in Figure 22 reveals that the water diversion volume at CP1 was 78% of the total river discharge, at location CP2 was 68% of the total river discharge whereas at locations CP3 and CP4 was 84% and

45%, respectively. Consequently, the simple weir at location CP5 was washed away by flash floods. It was discovered that well-maintained simple weirs diverted and withdrew amounts of water between 78% and 84% of the river's total flow and diverted it for irrigation downstream.

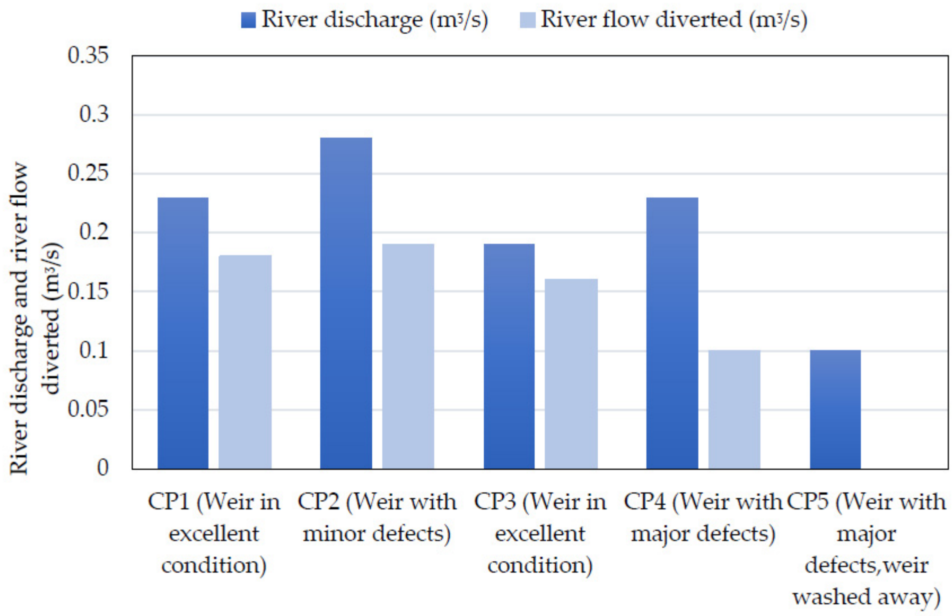

Figure 22. Weir condition, average river inflow, and water diversion volume.

The findings for North-Western province are shown in Figure 23. At location NW1, the water diversion volume was 75% of the total river inflows, at NW2 the water diversion volume was 80% of the total river inflows, whereas, at NW3, NW4, and NW5 the water diversion volumes were 87%, 63%, and 54%, respectively. The findings of this study also demonstrate that 90% of the simple weirs did not prevent water from flowing downstream for beneficial applications, including environmental flow requirements [36].

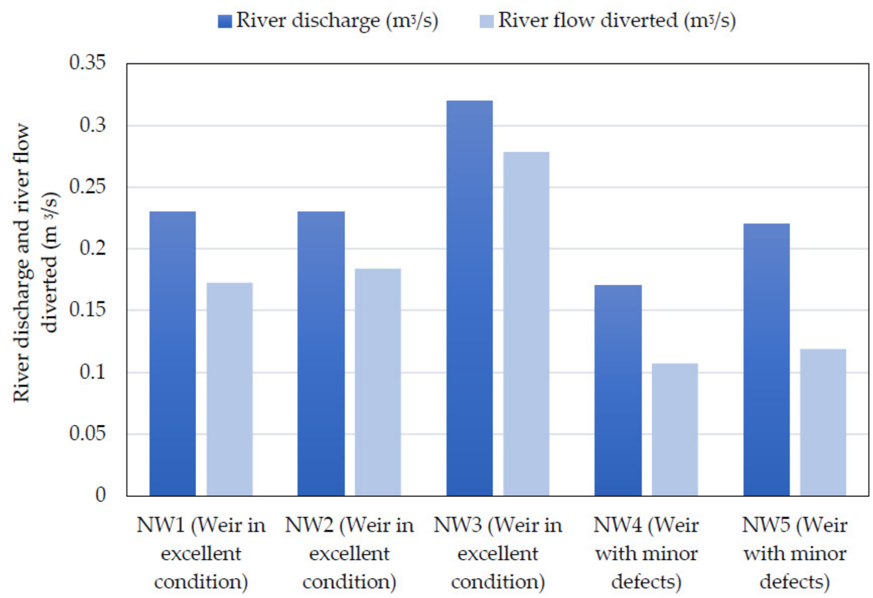

Figure 23. Weir condition, average river inflow, and water diversion volume.

4. Discussion

Some 502 simple weirs were constructed at different locations and on different rivers between May and August 2023. However, for this research, 15 simple weirs were selected for intensive rigorous investigation because of time limitations. The investigation details included: measurement of river inflows, river dimensions (width and depth), upstream water levels, water level changes, historical river flows, and percentage of flow diverted.

It was observed that these types of weirs are vulnerable to a range of factors including construction materials, river size (width and depth), river velocity, seasonal variation in river flow, precipitation, intake dimensions (width, depth, and slope), weir conditions, type of simple weir, downstream water demand, and soil type.

It was revealed that in the proper functioning of these structures, the water level upstream is an important factor. Because of seasonal variations in river flow, the river's water level fluctuates from season to season. The weir's restriction of river flow helps to stabilise the river's upstream water level. The aforementioned factors are linked to the amount of water discharged by the river into the canal. It was found that the majority of simple weirs improved the flow diverted into a canal built closer to the water intake point upstream; this was achieved by raising water to an average height ranging between 0.1 m and 0.5 m above the historic flood level at times of lowest river flow.

The advantage of these structures is that they can be constructed on a variety of river conditions to divert water. According to data gathered between November 2022 and January 2023, around 80% of the total number of operational single-line weirs diverted more than 70% of the discharge of their respective river flows. Further research has shown that 80% of single-line weirs in Luapula divert between 92% (0.18 m^3/s) and 70% (0.12 m^3/s) of the river flow, whereas only 60% of the single-line weirs in North-Western province achieved this.

5. Conclusions

The purpose of this study was to demonstrate that simple weirs are a model approach for small-scale irrigation development and promotion in rural areas in developing countries. This study examined a total of 15 simple weirs built by small-scale farmers in the remote rural provinces of Luapula, Copperbelt, and North-Western to determine the difficulties and the potential of these structures for redirecting river flow for irrigation. According to the evaluation's findings, 67% of all structures were in excellent condition, 27% had minor damage, and 6% had serious damage. These results correspond well with those from earlier research on comparable structures.

The other intriguing finding made in our assessments of these structures is that, with proper maintenance, simple weirs can achieve a water diversion efficiency of over 75%. This level of performance was achieved by about 10 out of the 15 simple weirs. In our evaluation of flow diversion, we found that some weirs diverted more than others. This may be attributed to leakages and seepages. The water losses due to these challenges may be evidence of a lack of regular maintenance of the structures.

Based on Figures 21–23, simple weirs may be used to identify functional potential sites for development into permanent weirs, as these types of structures are temporarily constructed by the farmers for the predicted demands of irrigated crops in the dry season. However, information on the hydraulic dynamics of simple weirs is rather inadequate. For example, the vortex effect largely caused by the circulation of flow has not been comprehensively elucidated within these types of structures.

According to the conclusions of this study, basic weirs have a good impact, which is appreciated by poor small-scale farmers, demonstrating that these sorts of structures provide irrigation choice options to small-scale farmers in distant areas wherein concrete or masonry are not economically or financially viable due to the small scale. Simple weirs have been utilised by farmers to transition from subsistence irrigation to medium-scale irrigation. With the farmers' increasing interest in utilising simple weirs in the early stages of their practice of irrigated farming, irrigation development is guaranteed.

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Conflicts of Interest: Authors Yoshihiro Sagawa and Yoshinao Adachi were employed by the company Sanyu Consultants Inc. The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

References

1. Burney, J.A.; Naylor, R.L. Smallholder Irrigation as a Poverty Alleviation Tool in Sub-Saharan Africa. *World Dev.* **2012**, *40*, 110–123. [CrossRef]
2. Mulenga, B.; Takao, N.; Haruhiko, H.; Yoshihiko, O. Participatory Irrigation Management Model and Proposal for Adoption in Zambia. *Rural. Environ. Eng.* **2003**, *2003*, 68–79.
3. You, L.; Ringler, C.; Wood-Sichra, U.; Robertson, R.; Wood, S.; Zhu, T.; Nelson, G.; Guo, Z.; Sun, Y. What Is the Irrigation Potential for Africa? A Combined Biophysical and Socioeconomic Approach. *Food Policy* **2011**, *36*, 770–782. [CrossRef]
4. Ngango, J.; Hong, S. Adoption of Small-Scale Irrigation Technologies and Its Impact on Land Productivity: Evidence from Rwanda. *J. Integr. Agric.* **2021**, *20*, 2302–2312. [CrossRef]
5. Kamwamba-Mtethiwa, J.; Weatherhead, K.; Knox, J. Assessing Performance of Small-Scale Pumped Irrigation Systems in sub-Saharan Africa: Evidence from a Systematic Review. *Irrig. Drain.* **2016**, *65*, 308–318. [CrossRef]
6. Fanadzo, M.; Ncube, B. Review: Challenges and Opportunities for Revitalising Smallholder Irrigation Schemes in South Africa. *WSA* **2018**, *44*, 436–447. [CrossRef]
7. Djagba, J.F.; Rodenburg, J.; Zwart, S.J.; Houndagba, C.J.; Kiepe, P. Failure and Success Factors of Irrigation System Developments: A Case Study from the Ouémé and Zou Valleys in Benin: Comparing Irrigation System Developments in Benin. *Irrig. Drain.* **2014**, *63*, 328–339. [CrossRef]
8. Chazovachii, B. The Impact of Small-Scale Irrigation Schemes on Rural Livelihoods: The Case of Paganai Irrigation Schemes Bikita District Zambambwe. *J. Sustain. Dev. Afr.* **2012**, *14*, 217–231.
9. Sinyolo, S.; Mudhara, M.; Wale, E. The Impact of Smallholder Irrigation on Household Welfare: The Case of Tugela Ferry Irrigation Scheme in KwaZulu-Natal, South Africa. *WSA* **2014**, *40*, 145. [CrossRef]
10. Mhembwe, S.; Chiunya, N.; Dube, E. The Contribution of Small-Scale Rural Irrigation Schemes towards Food Security of Smallholder Farmers in Zimbabwe. *Jàmbá* **2019**, *11*, 1–11. [CrossRef]
11. Xie, H.; You, L.; Wielgosz, B.; Ringler, C. Estimating the Potential for Expanding Smallholder Irrigation in Sub-Saharan Africa. *Agric. Water Manag.* **2014**, *131*, 183–193. [CrossRef]
12. Giordano, M.; De Fraiture, C.; Weight, E.; Van Der Bliek, J. *Water for Wealth, and Food Security: Supporting Farmer-Driven Investments in Agricultural Water Management. Synthesis Report of the AgWater Solutions Project*; International Water Management Institute: Colombo, Sri Lanka, 2012. [CrossRef]
13. FAO. *Irrigation Techniques for Small-Scale Farmers: Key Practices for Drr Implementers*; FAO: Rome, Italy, 2014; pp. 1–52.
14. Colenbrander, W.; Kabwe, A.; van Koppen, B. *Agricultural Water Management Technology Adoption in Zambia: An Inventory Report AgWater Solutions Project Case Study*; International Water Management Institute: Lusaka, Zambia, 2012.
15. De Fraiture, C.; Giordano, M. Small Private Irrigation: A Thriving but Overlooked Sector. *Agric. Water Manag.* **2014**, *131*, 167–174. [CrossRef]
16. Nilsson, E. *Socio-Economical Feasibility Study for a Proposed Weir on the Magoye River, Zambia*; Lund University: Lund, Sweden, 2012.
17. Atlas, W.I.; Housty, W.G.; Béliveau, A.; DeRoy, B.; Callegari, G.; Reid, M.; Moore, J.W. Ancient Fish Weir Technology for Modern Stewardship: Lessons from Community-Based Salmon Monitoring. *Ecosyst. Health Sustain.* **2017**, *3*, 1341284. [CrossRef]
18. Musuka, C.G.; Musonda, F.F. Contribution of Small Water Bodies and Small-Holder Aquaculture towards Poverty Alleviation and Enhancing Household Food Security in Zambia. *Int. J. Fish. Aquac.* **2013**, *5*, 295–302.
19. Singh, A.M. Modernization Farmers' Managed Irrigation Systems in Nepal. *Hydro Nepal* **2010**, *6*, 55–60. [CrossRef]
20. Richter, B.D.; Brown, J.D.; DiBenedetto, R.; Gorsky, A.; Keenan, E.; Madray, C.; Morris, M.; Rowell, D.; Ryu, S. Opportunities for Saving and Reallocating Agricultural Water to Alleviate Water Scarcity. *Water Policy* **2017**, *19*, 886–907. [CrossRef]

21. Rickard, C.; Day, R.; Purseglove, J. *River Weirs-Good Practice Guide*; Environmental Agency, Rio House, Water Drive, Aztec West: Bristol, UK, 2023.
22. Ngoma, H.; Hamududu, B.H. *Impacts of Climate Change on Water Availability in Zambia: Implications for Irrigation Development*; Michigan State University: East Lansing, MI, USA, 2019.
23. Jensen, M.E. Beyond Irrigation Efficiency. *Irrig Sci.* **2007**, *25*, 233–245. [CrossRef]
24. Hamududu, B.H.; Ngoma, H. Impacts of Climate Change on Water Resources Availability in Zambia: Implications for Irrigation Development. *Environ. Dev. Sustain.* **2020**, *22*, 2817–2838. [CrossRef]
25. FAO. *Aquastat Country Profile-Zambia*; Food and Agriculture Organization of the United Nations (FAO): Rome, Italy, 2005.
26. Akayombokwa, I.M.; van Koppen, B.; Matete, M. *Trends and Outlook: Agricultural Water Management in Southern Africa*; International Water Management Institute: Colombo, Sri Lanka, 2015.
27. Acharya, A.S.; Prakash, A.; Saxena, P.; Nigam, A. Sampling: Why and How of It? *Indian J. Med. Spec.* **2013**, *4*, 330–333. [CrossRef]
28. Taherdoost, H. Sampling Methods in Research Methodology; How to Choose a Sampling Technique for Research. *International Journal of Academic Research in Management* **2016**, *5*, 18–27. [CrossRef]
29. Bagheri, S.; Kabiri-Samani, A. Simulation of Free Surface Flow over the Streamlined Weirs. *Flow Meas. Instrum.* **2020**, *71*, 101680. [CrossRef]
30. Shariq, A.; Hussain, A.; Ansari, M.A. Lateral Flow through the Sharp Crested Side Rectangular Weirs in Open Channels. *Flow Meas. Instrum.* **2018**, *59*, 8–17. [CrossRef]
31. Ministry of Agriculture and Livestock. *Technical Cooperation Project on Community Bases Small-Holder Irrigation in The Republic of Zambia*; Ministry of Agriculture and Livestock: Lusaka, Zambia, 2017.
32. FAO. *Small Dams and Weirs in Earth and Gabion Materials*; Food and Agriculture Organization of the United Nations (FAO): Rome, Italy, 2001.
33. Ertiro, F.; Pingale, S.M.; Wagesho, N. Evaluation of Failures and Design Practices of River Diversion Structures for Irrigation: A Revisit of Two SSI Schemes in Ethiopia. *Int. J. Earth Sci. Eng.* **2017**, *10*, 495–505.
34. Sethaputra, S.; Kuntiyawichai, K.; Plermkamon, V.; Sawaengphet, J. Sizing of a Small Irrigation Weir. *Eng. Appl. Sci. Res.* **2017**, *44*, 3. [CrossRef]
35. Masseroni, D.; Castagna, A.; Gandolfi, C. Evaluating the Performances of a Flexible Mechanism of Water Diversion: Application on a Northern Italy Gravity-Driven Irrigation Channel. *Irrig Sci.* **2021**, *39*, 363–373. [CrossRef]
36. Government of the Republic of Zambia. *Agricultural Water Management National Situation in Zambia. Analysis Report of the AgWater Solutions Project*; Government of the Republic of Zambia: Lusaka, Zambia, 2009.