

*Review*

Assessment of Water Flow and Sedimentation Processes in Irrigation Schemes for Decision-Support Tool Development: A Case Review for the Chókwè Irrigation Scheme, Mozambique

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Abstract: Water flow and sedimentation processes have been significantly erratic at the Chókwè Irrigation Scheme (CIS) and have affected its hydraulic performance. Given its expansion there is need to understand these processes taking place on-site and along the channels of the scheme. CIS being the biggest project of its kind in Mozambique requires proper management of water flow and sedimentation processes. Therefore, the effect of water flow, sediment transport and deposition parameters on the performance of the CIS is needed. In order to determine the effect of spatial and temporal water flow and sediment distribution trends along the irrigation canals, there is need to establish a correlation between these parameters. Determining the influence of water flow velocity on sediment settling rate at different depths along the canal reaches is important in managing the CIS. In addition, a developed decision-support tool to predict sediment deposition is required. For this reason, it is therefore crucial to carry out a timely assessment of water flow and sedimentation processes in CIS in a review concept. From the current review, some gaps that exist for more focused research on Chókwè Irrigation Scheme have been identified. In this regard therefore, there is need to develop an effective support tool for managing water flow and sediment deposition along the canal reaches with a view to increasing crop production in CIS.

Keywords: Chókwè Irrigation Scheme; decision-support tool; hydraulic works; irrigation canal; sedimentation; water flow

1. Introduction

Improving water management of irrigation schemes through sediment management is required in order to achieve adequate water supply and food production [1,2]. Hydraulic and operational performance analysis is therefore important in irrigation canal systems, particularly in large systems having unlined canals, where sedimentation is common [3]. By having better details of water intake, reservation and distribution, the sedimentation analysis helps to identify constraint in hydraulic and operational performance which will inform on finding alternatives for improvement [4]. At the Chókwè Irrigation Scheme (CIS), water resources management challenges have been reported as being caused by a number of factors which include sedimentation.

Sedimentation reduces canal conveyance efficiency leading to inadequacy and inequity in water distribution to crops. In addition, sedimentation may lead to increased risk of canal breach due to reduction in freeboard and waterlogging [5]. Although a number of irrigation canals at the CIS have had their initial geometric shape design modified as a result of sedimentation, there is still limited work that has been carried out at CIS to minimize the problem. The only activity that has been common is the mechanical desilting which is performed only when there are demands by affected farmers.

To solve problems in water resources management, such as the ones facing the CIS, earlier identification of limitations will give higher possibilities of successful application of efficient and effective measures [6]. The hydraulic and operational performances of CIS are adversely affected by sediments deposition in the system. The CIS predominantly comprises unlined canals and as result is highly affected by the sedimentation which eventually affects water flow processes [7,8]. Therefore, concerns have been raised on how to tackle the sedimentation challenges at the CIS [9].

Sedimentation is a worldwide concern as it affects the design of irrigation systems and their operational performance. The slope of an irrigation canal taking off from the head works is usually smaller than that of the parent stream, to enable water to reach the points below the stream where irrigation is required [10]. With such a small slope, the canal is unable to transport the entire load especially when heavy sediment load enters in the canal system. In most cases, part of the load will be deposited in the canal itself [11]. This has also been reported in other studies where a number of irrigations schemes and rivers are affected by sedimentation leading to significant reduction in their capacity of water conveyance and delivery as well as blockage of hydraulic channels.

Notable irrigation schemes with huge challenges of sedimentation include: Coromandel region in New Zealand [12,13], Khoshi river system and Sunsari Morang Irrigation Scheme in Nepal [14,15], Elkhorn Slough Watershed and Upper North Santiam River Basin, Oregon in USA [16–18], Jatiluhur irrigation system, at Bekasi Weir Irrigation Scheme in Indonesia [19], at Magdalena river in Colombia [20] and Iguatu Experimental Watershed in Brazil [21].

Sedimentation has been reported as one of the major problems affecting irrigation schemes within the African region and Eastern South Africa, where Mozambique is located. A number of studies carried out in other irrigation schemes such as Southwest Kano Irrigation Scheme in Kenya [22], Metahara Scheme in Ethiopia [23–25], Gezira Irrigation Scheme in Sudan [5], in suburban tropical basin in Congo [26] and irrigation schemes in South Africa [27] indicate that these irrigation schemes are experiencing such problems.

Sedimentation in CIS is reported to have compromised the canals' efficiency by lowering it to an average magnitude of around 50% [28]. This therefore, demands significant investments to rehabilitate the entire system. Additionally, having low efficiency due to sedimentation, compromises water supply in the canals, which is critical to match with population growth demanding for more food [29]. In order to cope with high population growth, more food is required to meet such a demand. Therefore, an efficient irrigation scheme is widely seen as a major solution whereby, establishment of a system with good performance is critical [30,31]. Achieving this will require a deep understanding of the influence of water flow velocity on sediments settling time at different depths of the canal. Furthermore, analysis of spatio-temporal trends and development of a decision-support tool, is critical at the site as a contribution for better performance [32]. Therefore, CIS must be efficient and this is only achievable if canals hydrodynamics under sedimentation are well understood. In this research therefore, an assessment of water flow and sedimentation processes of CIS is undertaken for the purpose of coming up with a possible exploratory research to address related challenges.

2. Sedimentation in Irrigation Systems

Sedimentation is the process by which different sized particles are transported and deposited into the water bodies and any other points along the water flow paths [33]. Sediment transport starts when shear forces applied by the flow overcome the weight of the particle and in the process, detaches and initiates down-slope motion [25]. Depending upon the hydrodynamic conditions and

sediment characteristics particles may move in three different forms such as bed load, suspension and saltation processes [5].

Firstly, the bed load is the mode of transport of sediments where the particles glide, roll or jump in constant contact with the surface of the bed [34]. The bed load generally consists of coarser particles. It is very important in sediment transport as it controls the shape, stability, and hydraulic characteristics of the channel. Equations describing bed load are available from different authors work, and can be grouped into the following three types: Du Boys-type equations that utilize a shear stress relationship, Schoklitsch-type equations that utilize a discharge relationship, and Einstein-type equations that are grounded in statistical considerations of lift forces. Details on their distinctions are given by [25].

Secondly, in suspension process of sediment transport the sediment particles displace themselves by making large jumps, but remain (occasionally) in contact with the bed load and also with the bed [35]. The suspended load usually consists of finer particles, such as silt and clay. There are two states of suspended sediment transport, equilibrium condition [23,36], with no deposition and no scouring processes, and non-equilibrium condition [2], when either of the phenomena can take place. The theoretical approaches used to estimate suspended sediment discharge in streams are mainly the energy approach and the diffusion-dispersion approach. The diffusion-dispersion theory is recommended over the energy approach because experimental evidence indicated that it fits better to observed data [37]. The total load is the summation of the bed load and suspended load. A large number of relationships have been developed for total load prediction in the flow [16].

Thirdly, the saltation process of sediment transportation involves creeping and saltation motion that produces steady sediment transport. Work by [38] studied sediment transport in the creeping and saltation regimes. The authors found out that for the logarithmic profile, the saturated flux shows a quadratic increase with the strength of the flow, and for the parabolic profile, a cubic increase. These outcomes of the referred study are of relevance in the study at CIS, as the results give a potential to predict sediment settling velocity at different depths of the canal and bed load characterization.

Causes of sedimentation may include natural occurrence, changes in gradient, erosion and obstruction of canals. However, a thorough research work is required to confirm the real causes of sedimentation. Therefore, numerous studies dealing with sediment management in irrigation canals have been carried out worldwide. For instance, [39] found that sediment degradation and aggregation processes in irrigation canals on large extent depend upon the hydrograph of water and sediment discharge. This author also concluded that by adjusting intervals of the processes sediments can be transported into further areas for deposition. [40] investigated clearance works in Pakistan and found out that if the desilting campaign is done in the upper two-thirds of the canal, it can greatly improve hydraulic performance of the canals. [41] developed a methodology based on numerical modelling and successfully applied it on a secondary network in Pakistan while proposing improvements in the design and desilting processes as a tool for longer preservation of equity.

[14] evaluated the design of irrigation system in Nepal for different operation and maintenance plans and their effectiveness on sediment transport. The authors concluded that the system performance in terms of sediment transport depends on the management of the system, including the water delivery schedules, the operation of flow control structures and the maintenance conditions of the canals. [42] applied SETRIC (Sediment Transport in Irrigation Canals) model to simulate sediment transport in irrigation scheme in Nepal, while [19] applied the same model in an irrigation scheme in Indonesia. Both studies addressed the applicability and versatility of the model for different conditions of operation and sediment input in the irrigation canals. [43] developed a mathematical model and applied it to simulate sediment in irrigation canals and found out that it predicted well the non-uniform sediment movement in irrigation canals.

[15] found out that it is possible to reduce sediment deposition problem by proper design and management of the system. [25] suggested an improvement in the canal operation in a study of an irrigation scheme in Pakistan. This author found out that sediment deposits during low crop water requirement periods can be re-entrained during peak water requirement periods. [5] studied the impact of improved operation and maintenance on cohesive sediment transport in Sudan and found

out that the absence of proper maintenance activities and water management have a prominent role in increasing the deposition along the irrigation canals. Such studies have not been carried out in Mozambique. Most of these studies dealt with non-cohesive sediment, except [5] work which considered cohesive sediment. In addition, none of the accessed studies brought out insights on settling velocities at different depths for a given canal reach.

3. A Review of Sedimentation for the Chókwè Irrigation Scheme

3.1. Study Area

The Chókwè Irrigation Scheme (CIS) is located in the Limpopo River Basin (LRB), Chókwè District, Gaza Province in Mozambique, between latitudes 24°04'3" South and 25°01'35" South, and longitudes 32°40'1" East and 33°37'14" East. CIS is located at the Lower Limpopo River Sub-Basin (LLRSB) covering an area of approximately 84,981 km². It has a large area which is dominantly dry, with rainfall averaging between 500 and 600 mm/year. Rainfall events are concentrated between October and March. The population density is 18 persons/km² [44]. The Limpopo River originates from Central Southern Africa and flows generally eastwards to the Indian Ocean, traversing a terrain encompassing an altitude of 1600 m in South Africa (In Drakensberg Mountains) to the sea level in Mozambique [45]. Its length and drainage area are estimated at 1750 km long and 430,000 km² respectively, while the mean annual discharge at its mouth in Mozambique is 170 m³/s [44].

The CIS is the main irrigation scheme in Mozambique and gets its water from Limpopo River at approximately 45 m³/s. Water is diverted into unlined canals benefiting more than 12,000 farmers tilling approximately 33,000 hectares for food production [46,47]. The CIS is used to deviate, store, manage and distribute water to the local producers, which is made possible by using two hydraulic structures namely: Massingir dam and Macarretane weir, both located at the upstream. Agriculture is the main activity in the region and constitutes the backbone of the region, producing rice, maize and vegetables. Nearly 90% of the irrigation scheme is irrigated by gravity. Gravity flow system is the main form of water application through furrow and flood methods. The main crops in the region are: rice which is grown mainly during the wet season, vegetables grown during dry season and maize during both the wet and dry seasons.

3.2. Climate and Soils

The climate of the CIS is classified by [48] as semi-arid, mega thermal. This is referred to as a steppe climate with a dry period in winter. In the area, the average annual rainfall is 530 mm, reaching its peak of about 140 mm in February and a minimum of 10 mm in July. Limited rainfall makes the rain fed agriculture to be very risky due to limited available water. The annual average temperature is 23.6 °C, the wind speed is around 153 km/day or approximately 6.4 km/h and insolation is 7.9 h/day. The relative humidity has an annual average value of between 60%–65% [49]. The reference evapotranspiration (ET_o) according to Penman–Monteith exceeds the rainfall in every month, and is about 1400 mm [47].

Figure 1 shows the map of the Chókwè Irrigation Scheme, including hydraulic structures such as the Massingir dam and Macarretane weir.

The soils in the region consist mostly of marine formation, often with saline-sodic conditions, which require efficient drainage. The CIS has land of great fertility from deposition of materials transported by the river, a fact that leads to good yields without fertilization, in most areas. This fact maybe challenged if measures to control sedimentation are implemented after this study. In general, soils are predominantly clayey to clay-loam, heavy, compact, impenetrable and very abrasive, tending to alkalinity [47]. They are also considered to be deep (with an effective thickness greater than 1 m), with clay content of around 35%. The internal permeability is moderately rapid and lies between 7 and 10 mm/h, with a usable fraction of water ranging between 10% and 13% which varies with the content of organic matter and clay. The pH ranges from 7.0 to 7.3. These soils achieve high yields, but require careful monitoring [47].

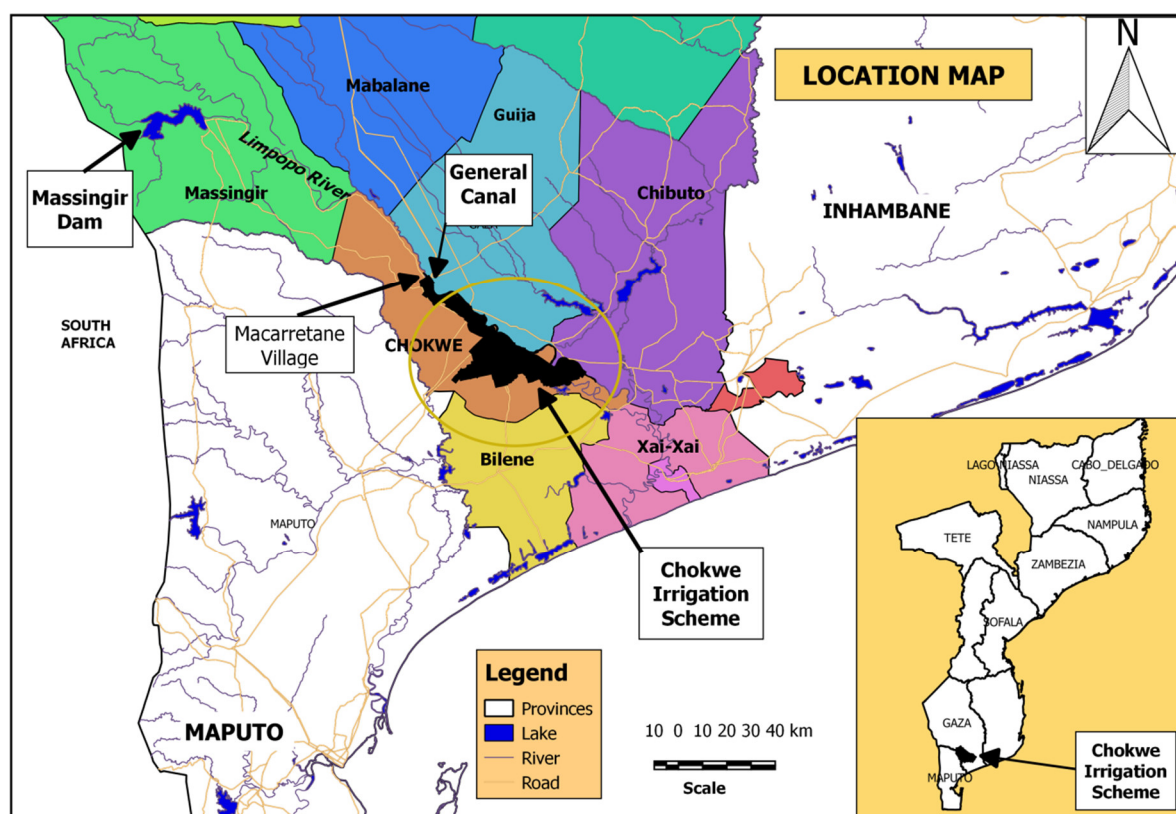


Figure 1. Location for Massingir dam, Macarretane weir and the Chokwe Irrigation Scheme. Source: Adapted from JAICA (Japan International Cooperation Agency) [50]

Sediment grain size characteristics and classification are related to the particles size distribution for a given sample. The sieve analysis is used for grain sizes of more than 0.063 mm (limit between sand and silt) [18]. The hydrometer test is conducted for fine materials (silt and clay). Dispersing agent, a solution of sodium hexametaphosphate (40 g/L of solution) to separate collides and to remove the organic matter can be used. Various sizes of sediment are classified according to United States of Geological Survey (USGS) as: clay sized particles (<0.004 mm), silt sized particles (from 0.004 mm to 0.062 mm), sand sized particles (from 0.062 mm to 2 mm) and gravel sized particles (2 mm to 64 mm) [51].

3.3. Hydraulics in the Irrigation Scheme

The CIS is composed of three main hydraulic sectors: Montante, Sul and Rio. Figure 2 shows the three main sectors of CIS. The hydraulic structures in the irrigation scheme include the Massingir dam, Macarretane weir, the main, secondary and tertiary canals, as well as the drainage network. Massingir dam is located nearly 130 km from Chokwe City and has a role to store water and convey it through Limpopo River stream to the Macarretane weir, at 30 km from Chokwe City [52]. Here water level is managed at the allowable height to continue its course to the CIS. These two structures play an important role in flood and drought management in the area.

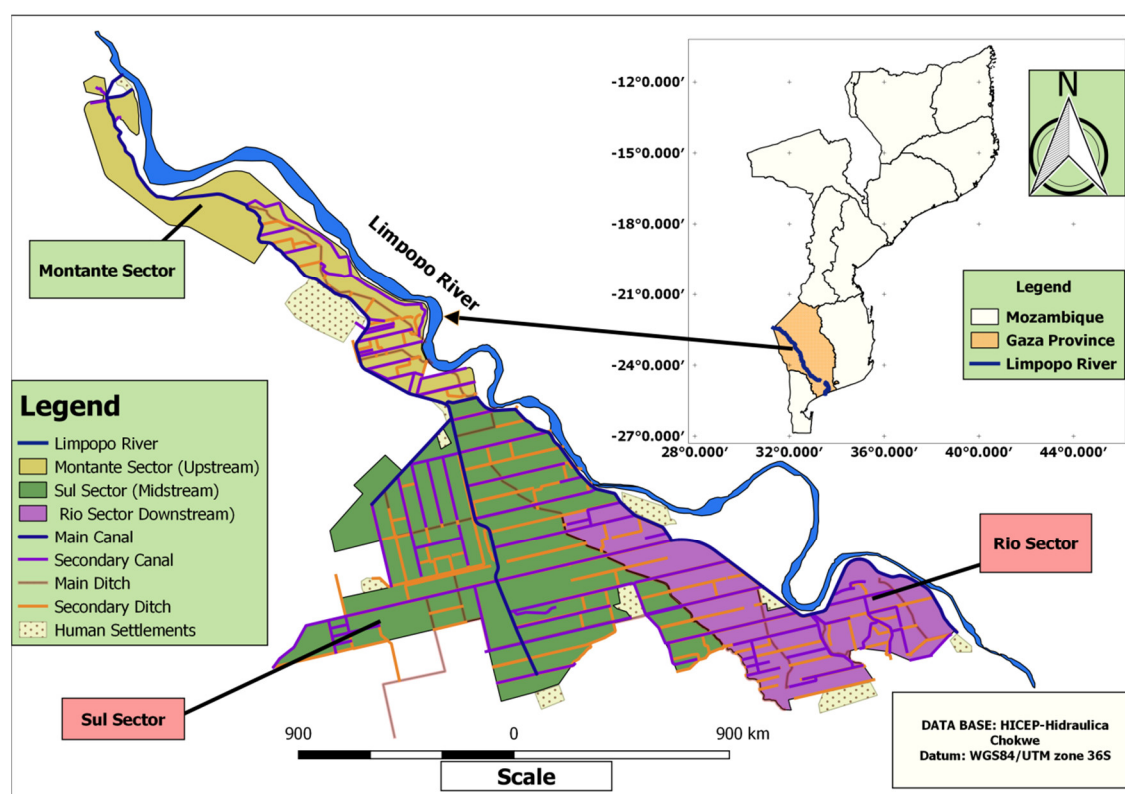


Figure 2. Map of the Chókwè Irrigation Scheme, in Mozambique. Source: HICEP (Hidráulica de Chókwè, Empresa Pública) [46]

In these sections, there are three levels of water conveyance (Figure 3) described as:

- i. **Main Hydraulic Units (MHU):** This includes a 75 km protection dike on the right bank of Limpopo River, Main unlined canals (*Geral, Rio, Direito* and *Nwachicoloane*), operating under upstream command. The total nominal discharges are between 4 and 45 m³/s, having a total length of 100 km. The main drains measuring 125 km cover a surface of 30,000 ha and others 3,000 ha are naturally drained. The MHU has main roads connecting to the National Road of nearly 155 km;
- ii. **Secondary Hydraulic Units (SHU):** Which includes 107 secondary zones, with 42 secondary canals (off-takes) directly supplied by the MHU. Its discharges vary between 0.1 and 4 m³/s with a total length of 270 km. The pumping and water distribution equipment are directly connected to the MHU canals, while the secondary drains measuring 450 km covering 27,000 ha, and the remaining 6,000 ha of the SHU are naturally drained. There are circulation roads over these secondary's networking of 175 km;
- iii. **Tertiary Hydraulic Units (THU):** This has prefabricated tertiary canals supplying water to the irrigation extensions, with unitary discharge of 32 L/s, and a total 1050 km of length. The THU has also trenches draining the extensions and providing access ways to the plots.

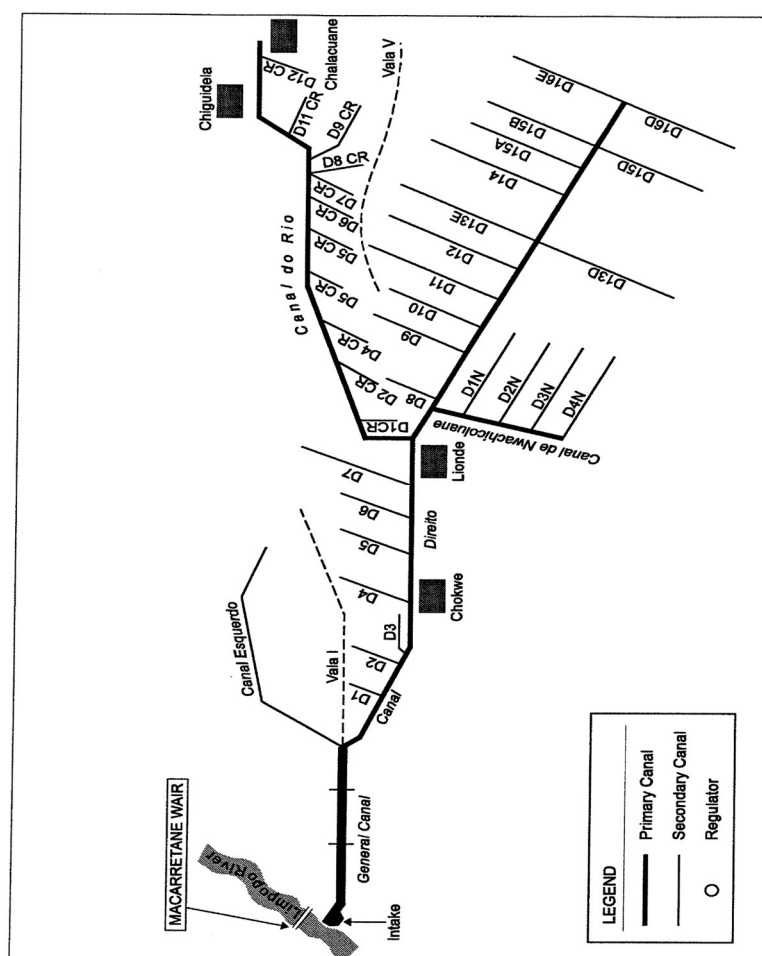


Figure 3. Main hydraulic units of the CIS. Where D= water distributors or secondary canals from where tertiary canals depart. Source: JAICA (Japan International Cooperation Agency) [50]

3.4. Sedimentation at the Chókwe Irrigation Scheme (CIS)

Work by [53] tested different scenarios for improvement of operational performance in CIS, using the DUFLOW (Dutch Flow) model and found out that by lowering the water level in the main system leads to an increase on the efficiency indicator. However, the study did not deal with sediment analysis. Therefore, there is still more work that is required to be done regarding sedimentation management, both non-cohesive and cohesive with a view to developing a tool for improving hydraulic and operational performance at CIS, in Mozambique. Work by [54] and by [55], using DUFLOW and HEC-RAS (Hydrologic Engineers Corps-River Analysis System) models respectively have shown great potential to describe hydraulic and operation conditions of river streams and irrigation canals using hydraulic models.

To predict the susceptibility of sedimentation within a given reach one needs to know the capacity of the channel to transport the material through the reach [56]. The sedimentation process may be investigated either by a forward physical approach or an inverse morphological approach [57]. The first approach involves use of known physics to predict sedimentation. The second is an inverse approach that uses the observed properties of the stream channel to infer sediment transport and depositional processes.

After many years of research in the field of sedimentation, no universally applied bed load transport function exists, given the uniqueness of each case and specific conditions of the experimental sites. However, a number of approaches to bed load transport have been investigated and are considered in this work. Furthermore, deposition of suspended sediment occurs when the fall velocity of the sediment is greater than the turbulent eddies suspending the sediment within the water column [58].

The forward approach can be used to predict the susceptibility of a canal section to sedimentation on the bed. The size and volume of background sediment supplied to the channel and the capacity of the channel to transport sediment downstream can be estimated. Sediment within the canal is transported through two main mechanisms as bed load and suspended load [59]. Suspended load is the material transported within the water column, while bed load is transported on the channel bed. The transport mechanics and therefore the fate of bed load and suspended load differ and are considered separately [34]. By understanding the mechanics of sediment transport and sedimentation, the variables that are most useful to the prediction of downstream sedimentation may be determined [60].

A forward model consists of a water flow source model, a hydrodynamic model and a sediment transport model. Forward models usually need bathymetry or topography data [61]. For water flow modelling, the initial flow and sediment influx can be calculated by using different models. A hydrodynamic model consists of several conservation equations to simulate the processes of water flow and sediment influx propagation and inundation [62]. Two different approaches can be considered to apply sediment transport model. Hydrodynamic and sediment transport models, are constructed as two separate modules. At each time step, the hydrodynamic model outputs hydrodynamic conditions to the sediment transport model [63]. The second one solves the system of equations that couples fluid dynamics and sediment transport. Furthermore, the morphological change simulated by the sediment transport model returns to the hydrodynamic model [61].

Forward physical models can be of one, two and three dimensions. Most of the forward models can simulate sediment transport processes during the water flow and sediment influx for mixed particle size. Commonly, the forward models separate bed load and suspended load, but some forward models consider the total load only [61].

The inverse approach uses channel morphology to provide information on the antecedent condition of the channel [64]. Channel morphology provides an integration of past conditions of sediment input, and discharge. It also provides information on the transport capacity of the channel where the supply limited channels have greater transport capacity than transport limited channels. There are different types of inverse problems and model parameters according to [61]. These model parameters include initial conditions, boundary conditions, sources and a mixture of the previous. A series of inverse methods including the direct method, trial-and-error manual calibration method and data assimilation algorithm have been proposed to solve inverse problems. Both trial-and-error inverse model and data assimilation inverse model consist of a forward model and an inverse method [62]. This method has the advantage for its ability to provide information based on the observed data rather than a prediction, as given on the forward physical models [61].

Besides these, at CIS, there is need to consider the canal beds. Canal beds are stable when there is a balance between driving forces and the factors (framework) resisting that erosion. Sedimentation or erosion occurs when there is an imbalance between the driving forces and the resisting framework within a stream channel. The authors of [65] proposed a function to describe the balance as:

$$Q \times S \alpha Qs \times D_{50}, \quad (1)$$

where,

Q = water discharge (m^3/s)

S = bed slope (m/m)

Qs = sediment discharge (m^3/s) and

D_{50} = median sediment size of the soil particles (mm)

This function, termed Lane's Law, balances the driving forces on one side against the resisting framework on the opposite side. Lane's stability concept equates the product of a canal's sediment load and sediment size with the product of the same canal's slope and discharge. The estimation of each component is described in the following sub-sections:

(a) Driving Forces

Lane's Law illustrates that the driving forces in channels increase with larger slope and greater discharge [57]. Bank full discharge (Q_{bf}) is commonly used as the dominant channel forming flow [66], which occurs when the canal stage reaches the floodplain level [67]. The energy at the channel bed available to do the work, calculated using the channel slope and discharge, is represented by stream power (Ω , W/m):

$$\Omega = \rho \times g \times Q \times S, \quad (2)$$

where,

Q = water discharge (m^3/s)

ρ = density of water (kg/m^3) and

g = acceleration due to gravity (m/s^2)

A related energy term is specific stream power (ω , W/m^2):

$$\omega = \frac{\rho \times g \times Q \times S}{w} = \frac{\Omega}{w}, \quad (3)$$

where,

Ω = normalized by channel width (w) (m)

An additional term describing the driving force is the shear stress at the bed (τ_o , Pa):

$$\tau_o = \rho \times g \times R \times S = \frac{\omega}{v}, \quad (4)$$

where,

R = hydraulic radius (m) ($R = A/P$, where A is the channel area (m^2), P is the wetted perimeter (m)) and

v = cross-sectional average velocity (m/s)

Then, a related variable to driving force is velocity (v , m/s). In this case, as velocity increases, the shear stress and stream power generally increase. Velocity can be estimated using Manning's equation:

$$v = \frac{R^{2/3} \times S^{1/2}}{n}. \quad (5)$$

(b) Resisting Framework

The resisting framework balances against the driving forces to limit sediment entrainment and transport [33]. One important aspect of the resisting framework is the grain size of the bed sediment. Materials with larger grain size offer more resistance to transport than smaller materials. Lane's Law uses the median grain size (D_{50}) to describe this effect. However, several other measurable parameters are used to describe the grain size including D_{16} and D_{84} (the sixteenth and eight-fourth percentile of the cumulative grain size distribution, respectively). For areas where it is impractical to measure grain size directly, like downstream of all crossings, grain size (D_{50}) can be estimated using a technique developed by [68] given as:

$$D_{50} = \frac{(\rho \times \alpha \times A^\beta \times S)^{1-n}}{(\rho_s - \rho) \times k \times g^n}, \quad (6)$$

where,

k and n = empirical values that vary with channel type and local catchment conditions

A = drainage basin area covered by the canal stream (m^2)

α and β = empirical values representing local physiography (geology, topography and climate), basin hydrology and sediment supply, and

g = acceleration due to gravity (m/s^2).

The critical shear stress (τ^*) is the threshold of shear stress on the bed required to initiate motion of a particle. The most common method used to relate particle grain size to the critical shear stress is the Shields equation [68] given as:

$$\tau^* = \frac{\tau_c}{(\gamma_s - \gamma) \times D_{50}}, \quad (7)$$

where,

τ^* = Shields parameter

γ_s = specific weight of sediment (N/m³) and

γ = specific weight of water (N/m³)

For gravel bed rivers, the Shields parameter typically ranges from 0.03 to 0.073.

The other factor from Lane's Law [57] is the sediment load (Q_s) or the total volume of sediment transported by a stream channel. A simple relation using the sediment discharge (Q_s) as a function of discharge (Q) is called a sediment rating curve which is expressed as:

$$Q_s = a \times Q^b, \quad (8)$$

where,

a and b = are coefficients [69].

A dimensionless rating curve has been developed by dividing Q_s by bank full discharge (Q_{bf}). Assuming that the coefficient a does not vary with Q_{bf} , this eliminates a from the equation. Although some authors have suggested average values for the exponent b , however b varies from one canal to another and is not predictive but may be calibrated for individual sites.

(c) Sediment Balance

Sediment load is not heterogeneous downstream and the effect of increasing sediment input to a stream bed can be accessed through the development of a sediment balance for every channel reach. The sediment balance can be defined as:

$$\Delta Q_s = Q_{s\ in} - Q_{s\ out}, \quad (9)$$

where,

ΔQ_s = change in sediment volume within a reach (m³)

$Q_{s\ in}$ = volume of sediment entering a reach (m³) and

$Q_{s\ out}$ = volume of sediment exiting a reach (m³)

Where ΔQ_s is equal to zero, the bed is stable (termed in grade), ΔQ_s is positive when the bed is aggrading (bed level increasing/sedimentation) and where ΔQ_s is negative when the bed is degrading (bed level decreasing/erosion).

(d) Bed Load Transport

Sedimentation on a channel bed is controlled by the sediment transport dynamics within the reach. After more than a hundred years of research on bed load transport, there remains no universal equation that provides a reliable estimate of the transported bed material in a flood or water flow. The size of the material transported depends on sediment input, sediment distribution and channel energy characteristics but, the bed load fraction is always the material that moves in contact with the channel bed [70]. In gravel-bed canals, displacement of particles occurs by different means depending on the duration of the contact between the river or canal bed and the particle. Generally, sediment particles can move by saltation (little jumps in the water column), rolling or sliding [71].

Most of the theories on bed load transport have been developed from flume experiments where flow is steady and uniform [57]. These experiments use a reductionist approach and do not translate well to the natural environment, especially in gravel-bed canals where bed forms affect the flow at different spatial scales [72]. The scientific community has persistently attempted a diversified approach to bed load transport [71] and it is argued that a combination of a deterministic approach and a stochastic process is better suited to the understanding of bed load transport processes [73]. Because of the non-cohesive nature of the bed material, the resistance to entrainment offered by the particle depends on its physical characteristics such as size, shape, mass, shape of particles around it and the bed structure. The particle remains on the bed by its weight while the forces that lead to the incipient motion form drag forces that act tangentially to the particle and the lift force. Drag is created by the friction of water and lift is created by pressure differences around the particle. Entrainment is proportional to the shear velocity, μ^* and is given as:

$$\mu^* = \sqrt{\frac{\tau_o}{\rho}} = \sqrt{g \times R \times S}. \quad (10)$$

Gravel-bed canals are characterized by bed material with a wide range of particle sizes. The structure of the bed and the presence of various particle sizes lead to complex relationships between particle size and the force needed for particle entrainment. Small particles will need higher force than expected to be entrained when they are shielded by larger particles, while larger particle can be entrained at lower force when they are protruding in the flow [74].

Bed load transport can be divided into three phases [72]. Each phase of transport is a function of bed load transport intensity and exceedance above the critical threshold of particle entrainment of the median particle size. Generally, bed load transport follows a power relationship with a mean hydraulic variable. However, the response of the bed load is highly variable within a flood and from one flood to another [75]. This can be explained by the intermittent nature of bed load transport. Variables that cause intermittency in gravel-bed canals include bed armour, sediment supply and sediment waves. Because of these variables, bed load transport is discontinuous even in steady flow conditions where one set of hydraulic conditions does not lead to one transport response. The intermittency is characterized by periods of intense transport rates and periods of low transport rates that return periodically.

This pulsation pattern of the bed load transport rate is seen over various time scales, from seconds to a season. Haschenburger [76] associated the peak of the pulsation to the movement of bed forms. The bed load transport signal is composed of movement at different time scales caused by the movement of individual particles and the displacement of bed forms where the amplitude is higher for the lower frequency part of the bed load process. The intermittent nature of bed load transport changes with flow conditions [77]. At low flow conditions, bed load transport is very intermittent and it tends to be less intermittent when flow conditions are higher.

As gravel-bed canals are composed of particles over a wide size range, the bed load rate is calculated for different sizes in the mixture. Bed material size is typically characterized using a cumulative frequency distribution of grain-size. The proportions of the size fractions are used to calculate the transport rate. If the bed mixture of the gravel-bed canal contains more than 40% sand, it is said that the bed is matrix-supported. When the bed has less than 25% sand, the bed is said to be framework-supported [15,78].

An additional factor is that gravel-bed canals exhibit vertical sorting. Surface material is coarser than the sub-surface material. The surface layer is therefore termed the armour layer because it has the effect of increasing the critical shear stress necessary for entrainment. The composition of the transported material is generally finer than the surface layer and closer to that of the sub-surface material [68].

Bed load transport rate is generally defined as the volume of sediment transport per unit of channel width [79]. Termed the unit sediment discharge (q_s), it is influenced by both flow and bed material variables. Generally, unit sediment discharge can be defined as a function of the force of the water (τ_o), water depth (d or y), grain size (D), specific water density (γ), sediment density (γ_s) and water viscosity (μ). Almost all bed load formulae belong to one of the three types in which the unit transport rate is related to either. The equations of Du Boys-type (1879), Schoklitsch-type (1934) and Bagnold-type (1980) are in the excess shear stress, excess discharge and excess stream power, respectively are as shown:

$$(\tau_o - \tau_c); \quad q_s = X' \times \tau_o \times (\tau_o - \tau_c), \quad (11)$$

$$(q_o - q_c); \quad q_s = X'' \times S^{3/2} \times D^{-1/2} \times (q_o - q_c), \quad (12)$$

$$(w_o - w_c); \quad q_s \cong (w_o - w_c)^{\frac{2}{3}} \times d^{-\frac{3}{2}} \times D^{-\frac{1}{2}}, \quad (13)$$

where,

X' and X'' = sediment coefficients (dimensionless)

d = flow depth (m)

S = slope (m/m) and

D = grain size (mm)

(e) Suspended Load Transport

The second mechanism of sediment transport occurs within the water itself. Suspended sediment is transported within the water column and generally consists of relatively fine sediment (sand to clay). Cohesion may be important as it leads to aggregation of particles [73]. Fundamentally, suspended sediment is transported as upward turbulent water motion supports suspended sediment in the water column [80]. Deposition occurs where the fall velocity of a particle is greater than the turbulent motion holding the sediment within the suspension. The fall velocity of a particle can be calculated using:

$$V_o = \frac{1}{18} D^2 \times g \frac{\rho_s - \rho}{\mu} \text{ for silt and clay } < 0.0063 \text{ mm (Stokes' Law),} \quad (14)$$

$$V_o = \sqrt{\frac{2}{3} D \times g \frac{\rho_s - \rho}{\rho}} \text{ for gravel } > 2 \text{ mm,} \quad (15)$$

where,

V_o = settling velocity (m/s)

D = grain size (mm)

ρ_s = sediment density (assumed to be 2650 kg/m³)

ρ = water density (1000 kg/m³)

μ = dynamic viscosity (affected by temperature) (N.s/m²)

Water velocity and grain size were related to the entrainment, transport and deposition of suspended sediment by Hjølstrøm [81] through the development of two curves, one for entrainment and another for deposition. The depositional curve shows the velocities at which sediment of a given size will deposit. Note that there is a large difference between the entrainment curve and the depositional curve for fine sediment. This means that sediment will be entrained at a much higher velocity than it will be deposited. This leads to sediment suspended in the water column often being deposited at a long distance from the source area [80]. However, deposition may also occur in a downstream pool or riffle depending on the local velocities at the time.

The concentration of suspended sediment is generally several orders of magnitude below its sediment transport capacity [59]. Therefore, the dominant control on suspended sediment concentration is the rate of supply. Suspended sediment concentrations change throughout a storm hydrograph and throughout the year. These temporal changes may create a hysteresis because the rate of fine sediment supplied to the flow is greater during the rising limb of the hydrograph compared to the falling limb [41]. Sediment deposited and stored on the channel bed between storms is entrained by the increasing velocities during the rising limb, leaving less sediment supplied to the flow during the falling limb [59].

4. Prediction of Sediment Deposition

Generally, the suspended sediment concentration increases with discharge in the form of the empirical relationship:

$$C_o = k \times Q^b, \quad (16)$$

where,

k and b = constants

However, discharge is not a direct control on suspended sediment concentration but instead provides a surrogate for the turbulent forces suspending the sediment. As was mentioned earlier, the supply of suspended sediment is highly variable, leading to considerable scatter on plots of suspended sediment concentration and discharge [82].

The suspended sediment yield is the total suspended sediment output from a canal system or river basin over a given time period [83]. Sediment yield is controlled by all the factors that produce sediment over the landscape. Prediction of sediment yield may therefore provide a measure of the

background level of suspended sediment supplied to a site. Suspended sediment yield can be predicted using a sediment yield curve [4]. Sediment yield curves plot sediment yield against drainage basin area [57].

$$\frac{L_d}{A_d} = k_s \times A_d^b \quad (17)$$

where,

L_d/A_d = unit-area sediment yield (tonnes)

L_d = average sediment load for the integral period of analysis (usually 1 year)

A_d = contributing drainage area (km²)

b = scale exponent (also called specific yield)

k_s = true regional unit-area yield constant

What is most useful is the prediction of the amount of sediment deposited on the bed given a set of conditions. A commonly used expression to predict the mass sediment deposition rate when only one size class is considered is:

$$\varphi = \frac{d\bar{C}}{dt} = \frac{w_s \times \bar{C}}{d} \times \left(1 - \frac{\tau_o}{\tau_{cd}}\right); \tau_o > \tau_{cd}, \quad (18)$$

where,

C = depth-averaged suspended sediment concentration (kg/m³)

d = water depth (m)

w_s = constant related to the free settling velocity (m/s)

τ_o = bed shear stress and is the critical shear stress for deposition (N/m²)

A related relationship was developed for fine sediment deposition using a re-circulating flume [84]. In this case the models predict the fraction of the sediment deposited on the bed (f_d) for a given bed shear stress (τ_o) and grain size, related to the critical shear stress for deposition (τ_{cd}). The mathematical form of the deposition function is given as:

$$f_d = 1.0 - 0.325 \times \left(\frac{\tau_o}{\tau_{cd}} - 1\right)^{0.469} \quad \text{for } \left\{1 > \frac{\tau_o}{\tau_{cd}} < 12\right\}, \quad (19)$$

$$f_d = 1.0 \quad \text{for } \left\{\frac{\tau_o}{\tau_{cd}} < 1\right\}, \quad (20)$$

$$f_d = 0 \quad \text{for } \left\{\frac{\tau_o}{\tau_{cd}} > 12\right\}. \quad (21)$$

When the bed shear stress is much greater than the critical shear stress for deposition (for which $\tau_o/\tau_{cd} > 12$) no deposition occurs but when the critical shear stress is greater than the bed shear stress all the sediment is deposited. When the ratio of τ_o to τ_{cd} is between 1 and 12, part of the suspended sediment is deposited [85]. The critical shear stress for deposition is related to the grain size of the material in suspension. Therefore, the size of the sediment that is supplied to the channel is critical in understanding the fate of sediment entering the system.

5. Possible Solutions to Sedimentation Problems

Sediment management and control strategies start with the selection of a proper point for the diversion and the choice of appropriate structures at river intakes in order to prevent unwanted sediment entry into the irrigation canals. Sediments that enter into the canals are ejected through different means. In most cases, this is done by the structures or sometimes sediments are deposited in the oversized canal sections, settling basins or at the head of the canals. Further, the canals are so designed that the hydraulic conditions during canal operation allow neither sediment deposition nor scouring in the canal prism. The off-taking structures are designed for maximum withdrawal of the sediments from the main canal depending upon the command areas. Then the canal operation is planned in such a way that either of the phenomena is inhibited.

Irrigation canal systems can be operated under fixed or flexible supply based approaches. In fixed supply based operation, canals always run at full supply discharge and such operation,

generally, does not allow sediment deposition in the canal network due to sufficient high velocities. Whereas in demand based flexible operation, the canals do not run always at full supply discharge but instead the discharge keeps on changing, depending upon the crop water requirement in the canal command area. Such a type of canal operation is not always favourable to sediment transport as under low discharges, flow velocities fall quite low and hence sediment deposition occurs in the canal system.

Apart from the above details, when searching for best options to manage the sediment deposition in an irrigation canal for any scheme, it is advisable to consider desilting of irrigation canals practices which should focus on:

- (i) The effect of sediment transport on upstream controlled irrigation canals intake;
- (ii) The effect of sediment transport on the hydraulic performance of downstream uncontrolled irrigation canal (effect of sediment deposition on sediment transport capacity);
- (iii) The effect of different operation on sediment transport (effects of design discharge, effects of existing discharge, and effect of different options of Crop Based Irrigation Operations (CBIO) on sediment transport);
- (iv) Management options, such as operation under different discharge conditions (operation under design discharges, operation under existing discharges, operation under CBIO model, target water level and sediment transport and Aval-Surface (AVIS) and Aval-Orifice (AVIO) gates' responses).

The AVIS and AVIO gates are similar gates. The name "AVIS" has a French background: AV is from "aval" and means downstream, and "S" is from "surface", whereas in "AVIO" the letter "O" is from "Orifice". The oval-surface gate operates at a free surface flow and orifice gate operates as an opening conditions [86]. Further, two types of both of these gates which are the "High Head" type and "Low Head" type are available. The High Head gates have a narrower gate than the Low Head gates with the same float. The High Head gates are usually employed in the irrigation canals where narrow canal cross-sections are required. The choice between the open type (oval-surface gates) and the orifice type is solely determined by the maximum head loss likely to occur between the upstream and downstream-controlled water levels [25].

Sediment management approaches in irrigation canals include sediment control at intake (by selection of point of diversion and the angle of diversion), sediment diverters or silt excluders (tunnel type sediment diverters, guide vanes, sand screens, pocket and divider walls, guide banks and training walls), sediment ejectors (tunnel type ejectors and vortex tube ejectors), settling basins, operation and maintenance of silt affected irrigation canals, flow control in irrigation canals (upstream control, proportional control and downstream control), sediment control by canal design approach (lined canals, unlined canals, Kennedy's regime concept and Lacey's regime equations, maximum permissible velocity method, tractive force method and the hydraulic design criteria (HDC). The Lacey equations are as given by [78] in Table 1.

Table 1. Important equations in water and sediment fluxes.

S.No	Equation	Equation Author	Equation Number
1	$P = 4.84\sqrt{Q}$	Lacey	(22)
2	$U = 0.625\sqrt{fR}$	Lacey	(23)
3	$S_o = 0.0003 \frac{f^{5/3}}{Q^{1/6}}$	Lacey	(24)
4	$f = \sqrt{2500d}$	Lacey	(25)
5	$\tau = c\rho gyS_o$		(26)

where, P = wetted perimeter (m), R = hydraulic radius (m), d = sediment size (m), U = mean velocity (m/s), S_o = bed or bottom slope (m/m), f = Lacey's silt factor for sediment size d , Q = discharge (m³/s),

τ = shear stress (N/m^2), c = correction factor depending upon the B/h ratio (B for canal width) and for wide canals $c = 1$, y = water depth (m), ρ = density of water (kg/m^3), g = acceleration due to gravity (m/s^2)

6. Conclusions and Recommendations

The present study aimed at assessing the water flow characteristics and effects of sedimentation, available methods of sedimentation analysis and gaps in sedimentation studies in the Chókwè Irrigation Scheme. This work has identified key gaps to address the challenges of water flow and sedimentation into CIS. Out of this assessment and review work, a need has been established to formulate a decision-support tool for sediment and water flow prediction and management in the CIS. From the study it is recommended that:

- (i) Determination of the effect of physical, hydraulic and sediments transport and deposition parameters on the performance of the Chókwè Irrigation Scheme be conducted for creation of awareness;
- (ii) Assessment of the spatial and temporal water flow and sediment distribution trends along the canals of the Chókwè Irrigation Scheme for the period of the last fifteen years be explored for planning purposes;
- (iii) Modelling of the influence of water flow velocity on sediments settling time at different depths of canal sections using HEC-RAS and SIC² models for the Chókwè Irrigation Scheme be carried out;
- (iv) Developing of a decision support tool to predict sediment deposition using HEC-RAS and SIC² models for the Chókwè Irrigation Scheme be done.

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