Chapter 4

Assessment of the Riparian Vegetation Changes Downstream of Selected Dams in Vhembe District, Limpopo Province on Based on Historical Aerial Photography

John M. Mokgoebo, Tibangayuka A. Kabanda and Jabulani R. Gumbo

Additional information is available at the end of the chapter

http://dx.doi.org/10.5772/intechopen.78329

Abstract

Dams have been associated with various impacts on downstream river ecosystems, including a decrease in stream flow, species biodiversity, water quality, altered hydrology and colonisation of the area by invasive alien plant species. The impacts normally interfere with the ecosystem functioning of riparian and aquatic environments, thereby leading to decreased biodiversity. This study aims to assess the impacts of dams on downstream river ecosystems, using data from aerial photographs and orthophotos, supplemented by field work. Five dams in Limpopo Province, South Africa, were selected (Albasini, Damani, Mambedi, Nandoni and Vondo), and photographs from different years were used. The area devoid of trees of certain species both downstream and upstream of the dams was calculated using grids of predetermined square sizes on each available photograph. Aerial photographs and orthophoto data were supplemented by field work. The nearest-individual method was used in the field to determine tree density of particular tree species. The environments downstream of the dams show a loss of obligate riparian vegetation and an increase of obligate terrestrial vegetation (*Acacia Karroo, Acacia Ataxacantha* and *Bauhinia galpinii*). Treeless area increased in all cases, especially in the case of Mambedi and Vondo dams, indicating lower resilience and higher fragility there.

Keywords: downstream, upstream, aerial orthophoto, riparian vegetation, damming of rivers

1. Introduction

Dams across the world have been associated with many negative environmental, social and economic impacts. In particular, dams tend to affect downstream water flow, leading to vegetation species loss. Many dammed rivers around the world have been characterised by decline in species biodiversity, increase in invasive alien plants and pollution. Mumba and Thompson [1] argue that flow disturbance provides stimulus for the establishment of opportunistic plants, particularly alien invasive species. In Limpopo, the most northerly province of South Africa, the impacts of dams have also been accelerated by the alternating wet and dry climatic conditions that greatly affect the flow regimes of rivers. This is because dams create barriers to natural water flow and interfere with ecological processes of riparian zones that influence vegetation composition, richness and diversity [2]. Dams have been associated with water pollution generated from industries and agricultural sectors, such as the release of litter, hot water, pesticides and fertilisers into streams and rivers [3].

The decrease in downstream flow is strongly associated with negative impacts on downstream riparian ecosystems. The decrease in water quality and quantity downstream alters the vegetation composition, natural irrigation of floodplains and microclimates. These downstream impacts are associated with a decrease in biological diversity, changes in successional stages, altered biogeochemical cycles and alteration of downstream natural ecosystems. Toxins that accumulate in dams can be released during flush periods and is often accompanied by irreparable damage to the downstream environment. The presence of dam results in landscape modification and changes in hydrology, channel morphology and physiochemical properties result in the dramatic decrease in biodiversity in riparian and aquatic ecosystems (upstream & downstream) [4]. About half of South Africa's rainfall is stored in dams [5]. There are about 550 government dams that carry about approximately 37 million m^3 of water. There are about 25 registered dams in Limpopo Province [6].

The dams of Limpopo, with much of the Province characterised by wet-dry climatic cycles have remarkable and sometimes irreversible impacts on downstream ecosystems. These dams usually change vegetation composition, reduce species diversity, alter flow characteristics and encourage alien species invasion that alter the ecosystem functioning of rivers downstream. Need therefore arises that the impact of these dams on their downstream river ecosystems be studied using historical aerial photograph data to determine whether the upstream existence of dams impacts on downstream vegetation density. The main purpose of the study was to use historical aerial photography to assess the impact of selected Luvuvhu/Mutale dams of the Limpopo Province on their downstream river ecosystems. The specific objectives were to study the nature of vegetation changes along downstream river courses, and to compare upstream and downstream vegetation species richness.

2. Materials and methods

The study area is riverine vegetation that is located upstream and downstream of the following dams: Albasini, Nandoni, Damani, Mambedi and Vondo dam that are located in Vhembe

http://dx.doi.org/10.5772/intechopen.78329

district, Limpopo province of South Africa. The major rivers Luvuvhu and Mutshindudi originate from Soutpansberg Mountains and the vegetation types range from co-regions 2.01 Sour Lowveld Bushveld, Soutpansberg Arid Mountain Bushveld and patches of Afromontane Forest to the eco-regions to 2.15 Northeastern Mountain Grassland and Afromontane Forest [8].

2.1. The study area

2.1.1. Albasini dam

The dam is situated at 23°06′25″S and 30°07′30″E. It was built on the Luvuvhu River in 1952 and was raised by means of spillway gates in 1970/1971. The dam was built to supply water to the Levubu Irrigation Scheme to irrigate tropical fruits such as bananas, litchis, mangos, avocados and macadamia nuts (**Figure 1**). Its maximum water carrying capacity is 25.6×10^6 m^3 [6]. It lies 22 km south-east of Makhado (formerly Louis Trichardt) and approximately 45 km west (upstream) of the Nandoni dam, which also lies on the Luvuvhu River. It has a surface area of 350 ha. The rainfall station in the vicinity of the dam is Goedehoop.

2.1.2. Damani dam

The Damani dam is on the Mbwedi River and was established in 1991 (**Figures 1** and **2**). The dam is situated at 22°50′07″S and 30°31′22″E and was built to supply water to the former Damani Coffee Estate which required $4.08\times10^6 m^3$ per annum. It supplies irrigation water to the surrounding commercial farms owned by local community members. Its maximum water carrying capacity is 12.4×10^6 m^3 and it has a surface area of 130 ha [6].

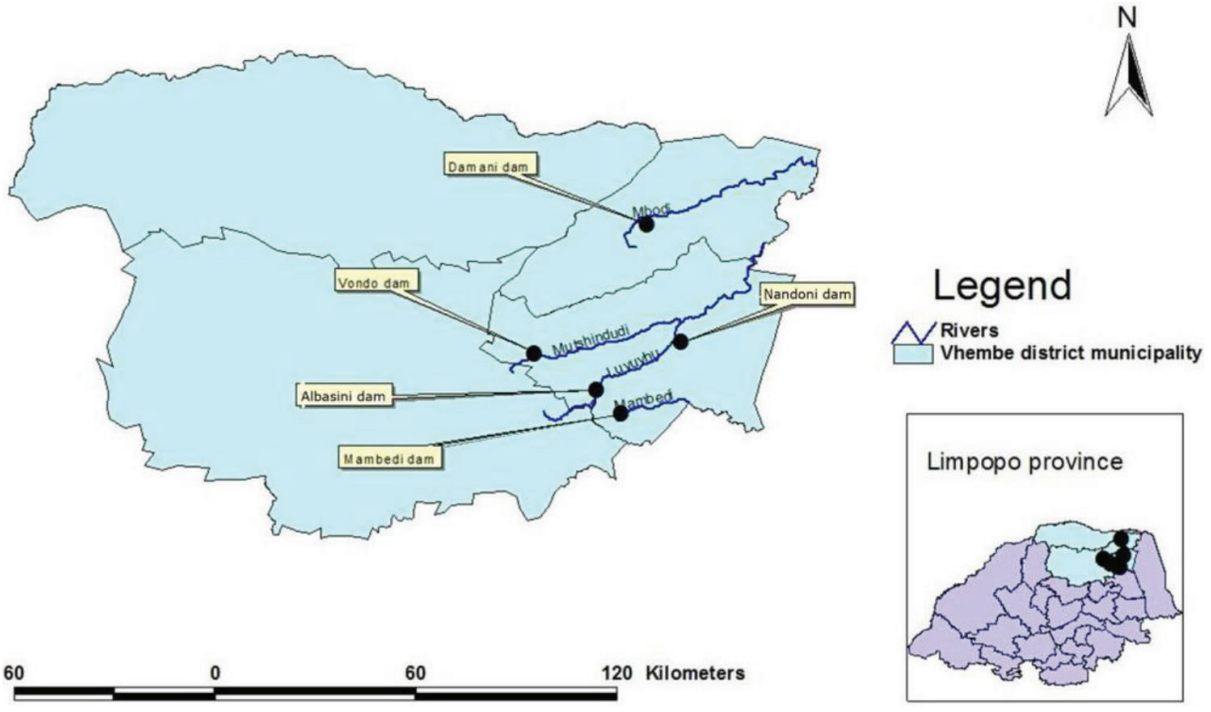

Figure 1. The locations of selected dams in the study area.

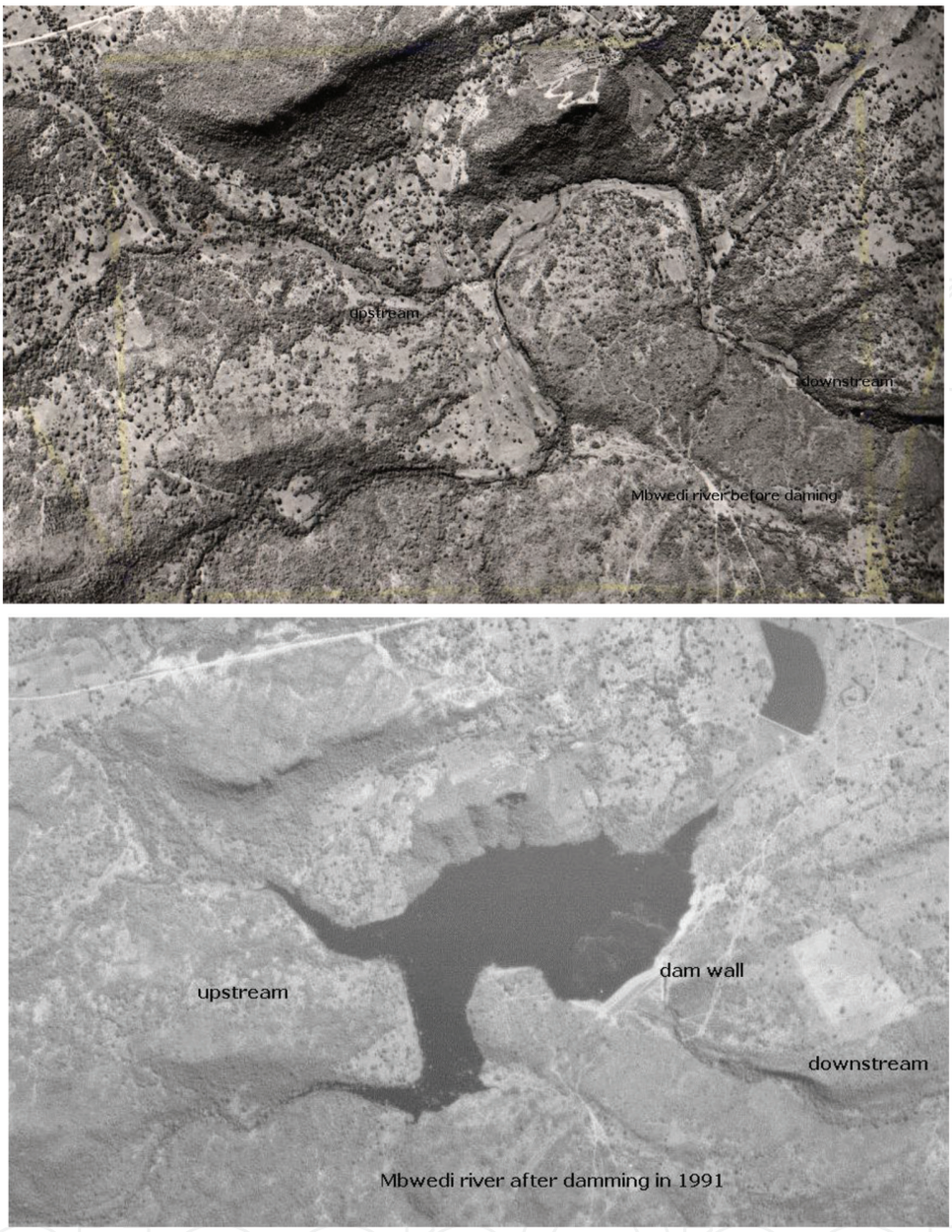

Figure 2. The riverine vegetation along Mbwedi River before the damming (top) and after construction of the Damani dam (bottom).

2.1.3. Mambedi dam

The dam was built on the Mambedi River to supply water to the Sapekoe Tea Company. The dam suffered a partial collapse in the year 2000 after its wall failed to contain an increase in flow during the heavy downpour caused by cyclone Eline. The dam had a carrying capacity of 7×10^6 m^3 prior to its collapse. This left the dam completely non-functional. The dam is situated at 23°07′27″S and 30°13′13″E [6].

http://dx.doi.org/10.5772/intechopen.78329

2.1.4. Nandoni dam

The Nandoni dam lies on the Luvuvhu River and was constructed in 2005. The dam is situated at 22°56′ 45″S and 30°20′07″ E. It was completed in 2009 and its water carrying capacity is $163\times10^6 m^3$ [6]. The dam has a surface area of 1570 ha. The Nandoni dam lies 40 km east (downstream) of the Albasini dam. It was built to supply water to the Nandoni water works and provide water for small scale irrigation [6].

2.1.5. Vondo dam

The Vondo dam was established in 1982 on the Mutshindudi River near Thohoyandou and Sibasa. The dam is situated at 22°56′45″S and 30°20′07″E. It has a capacity of 30.54×10^6 m^3 and a surface area of 219 ha. It was built to supply water to the Tate-Vondo Tea Estate [6].

2.2. The characteristics of the vegetation in the selected study area

A check sheet for vegetation data was used. This was used to record data on vegetation type, morphology and density. Data for these variables were collected both upstream and downstream of the dams. Before the actual collection of data a pilot survey was done to record the type of vegetation found along the major river courses of the Luvuvhu and Mutale river catchment. This was done to study the ecological setting of the study area and to identify points where data were to be sampled. Vegetation was categorised into trees, shrubs and herbs. All three life forms where identified in the field and measurements were done to determine pattern of vegetation change and density both downstream and upstream of the dams. Pattern of change was identified by studying vegetation composition along riparian zones both upstream and downstream of the dams to compare vegetation composition associated with water-deficient (downstream) and water-rich (upstream) environments. This was done to establish whether there was an increase in terrestrial vegetation along dry and wet riparian zones and to assess changes in morphological characteristics of the vegetation (whether short, dispersed or clustered).

Tree density was considered as the concentration of *Acacia* tree species within a given area, expressed in square meters. The nearest individual method of Kent and Coker [7]) and the simple plotless sampling was carried out to measure tree density. Since the study area was characterised by tall, dense and sometimes scattered trees, plotless sampling as a form of random sampling was used. Dense, sparse and tall tree species of the area limited the use of quadrants and other probabilistic sampling methods. With plotless sampling, sampled points were randomly selected using random walk procedures. These sampled points are called random walk points. The random walk points were chosen using random numbers selected from a random number table. The first selected random number represented the direction of the location of the random walk point. A standard prismatic compass was used to measure the direction of the randomly selected spots, ranging from 0 to 360°. The second random number represented the distance that was travelled to locate a sampled point, in the direction that was previously chosen. Tree density measurements were taken at 16 random walk points around each dam – 8 upstream and 8 downstream of the dam.

All the random walk points were used as starting points to measure tree density using the nearest individual method. For each selected spot a total of five distance measurements were taken and all measurements were averaged to determine the mean distance of each tree species from the random walk point. Acacia tree species were used for the purpose of this measurement. A 30 m tape was used to measure distances from selected random walk points to the nearest individual tree species. Five distance measurements between similar individual species, per random walk point, were taken and averaged to determine the mean distance of individual tree species from the random walk points. All distances were then averaged and squared to determine the mean area of Acacia tree species using a formula (1) adapted from Kent and Coker [7] as follows:

$$A = N^2 \tag{1}$$

where A is the mean area of tree species and N is the mean distance to the nearest individual species.

After the calculation of mean area, tree density was also calculated using a formula (2) adapted from Kent and Coker [7] as follows:

$$TD = \sqrt{\frac{A}{2}} \tag{2}$$

where TD is the tree density.

2.3. The use of aerial photographs and orthophotos for treeless cover area

Tree cover was defined as the extent of tree canopy cover in relation to the ground surface. The identification of trees on aerial photographs (**Table 1**) was based on size, shape, tone or shades of grey, pattern and texture.

To reduce bias and error in object identification a stereoscopic view was generated for adjacent aerial photographs to verify the shape, sizes, texture, pattern and tone of trees as suggested by Jensen [8]. Vertical aerial photographs (1:16,666) and orthophoto maps (1:10,000) of Luvuvhu/Mutale area were used to calculate the size of treeless area in all studied dams. These scales were chosen because they are able to show many landscape features and minimise misinterpretation of features. Booth et al. [9] argue that the accuracy of land or vegetation characterisation from remote sensing data is a function of spatial resolution. They recommend the use of the lowest-resolution photographs (1:60,000 to 1:40,000). This is why in this study of dams in the Luvuvhu and Mutale river catchment, the resolutions of 1:10,000 and 1:16,666 were used to study vegetation density changes both upstream and downstream of the dams. Orthophotos (=) (1:10,000) were also used because they were considered more accurate and could supplement measurements and object identification from vertical aerial photographs. Cameron et al. [10] argue that orthophotos are in fact rectified photographs showing objects in their true planimetric positions. The size of treeless area was considered to be the total surface area devoid of trees in a given area. The size of treeless area in each photograph was

http://dx.doi.org/10.5772/intechopen.78329

Aerial photographs for job number 908 of 1987			
Strip number	**Photo number**	**Area**	**Scale**
10	163 & 164	Damani	1: 16 666
11	364 & 365	Vondo	1: 16 666
12	274 & 275	Nandoni	1: 16 666
Aerial photographs for job number 932 of 1989			
2	2068 & 2070	Albasini	1: 16 666
Aerial photographs for job number 982 of 1995			
7	392 & 393	Damani	1: 16 666
9	108 & 109	Nandoni	1: 16 666
9	113 & 114	Vondo	1: 16 666
11	184, 185, 186, 187, 188 & 189	Mambedi & Albasini	1: 16 666
1: 10 000 orthophotos			
Title			**Area**
2330 AA 7 STERKSTROOM			Albasini
2330 AA 12 WOLVEROODE			Albasini
2330 AA 13 RIVERSANDS			Albasini
2330 AA 14 DRIEFONTEIN			Albasini
2230 DC 6 TSHIRONGA			Damani (Mvuwe)
2230 CD 10 MUHUYU			Damani (Mvuwe)
2230 DC 11 VONDWE			Damani (Mvuwe)
2230 CD 15 NGWENANI			Damani (Mvuwe)
2230 AA 14 MVUWE			Mambedi
2230 AA 15 BEAUFORT			Mambedi
2230 DC 21 MPHEGO			Nandoni
2230 DC 22 MPONDI			Nandoni
2230 DC 23 MAKUMEKE			Nandoni
2330 BA 1 DIDIDI			Nandoni
2330 AA 15 BEAUFORT			Nandoni
2230 CD 17 VHUSHAVHELO			Vondo
2230 CD 18 VONDO			Vondo
2230 CD 22 KHONGORONI			Vondo
2230 CD 23 MAPATE			Vondo

Table 1. Aerial photographs and orthophotos for Luvuvhu and Mutale dam areas (surveys and mapping: Department of Land Affairs).

calculated within an area of 4.5 km^2 both upstream and downstream of dams making a total surface area of 9 km^2 for each dam. This size of an area was chosen because it was possible to determine any tree cover variations between downstream and upstream sections of the dams.

On the aerial photographs of a scale of 1:16,666, a grid of 0.2 cm squares, with 4125 squares, was used to calculate the total surface area devoid of tree species both downstream and upstream of the dams. The size of the grid was 15 cm × 11 cm, equivalent to 2.5 km × 1.8 km on the ground, which is the total surface area of 4.5 km^2. All squares with no tree species were added together to obtain the total surface area devoid of tree species. The total number of squares with no tree species was then converted to square kilometres to determine the size of the area on the ground that was devoid of trees. The total surface area (3) devoid of trees was calculated as follows:

$$\begin{aligned} A &= S^2 \\ &= \frac{0.2 \times 16,666}{100,000} \times \frac{0.2 \times 16,666}{100,000} \\ &= 0.033\ \text{km} \times 0.033\ \text{km} \\ &= 0.001089\ \text{km}^2 \times 4125\ (\textit{number of sample squares}) \\ &= 4.5\ \text{km}^2 \end{aligned} \tag{3}$$

where ***A*** is the total surface area of one sample square, ***S*** is the one side of a square.

From the given formula, the total number of squares that contained no tree species was multiplied by 0.001089 km^2 to determine the total surface area devoid of tree species in km^2.

For the available 1:10,000 orthophoto maps, a grid of 0.25 cm square size was used with a total square of 7200. The size of the grid was 25 cm × 18 cm, which is an equivalent of 2.5 km × 1.8 km on the ground. Each square represented a total surface area of 0.000625 km^2. Therefore, the total surface area covered by the grid can be simplified as 0.000625 km^2 × 7200 to represent 4.5 km^2. The total surface area (4) devoid of trees was also calculated as follows:

$$\begin{aligned} A &= S^2 \\ &= \frac{0.25 \times 10,000}{100,000} \times \frac{0.25 \times 10,000}{100,000} \\ &= 0.025\ \text{km} \times 0.025\ \text{km} \\ &= 0.000625\ \text{km}^2 \times 7200\ (\textit{number of sample squares}) \\ &= 4.5\ \text{km}^2 \end{aligned} \tag{4}$$

2.4. Data analysis

The remotely sensed data was analysed qualitatively by describing the vegetation cover on aerial photographs and orthophotos. Tree cover from the remotely sensed images was described based on Dansereau's method [11] of vegetation description of physiognomy and structure as highlighted by Kent and Coker [7]. The method of Dansereau [11] describes cover based on the following criteria:

Barren (b): An area characterised open land with no trees and grass, or sparse trees of poor quality.

Continuous (c): An area characterised by uniform, unbroken dense vegetation cover.

Discontinuous (i): An area characterised by dense, but intermittent, cover. The interruption occurs as a result of in environmental gradients (slope, altitude, topography) and disturbed or degraded surfaces.

Tufts and groups (p): Bushes growing in clusters or groups, and is separated from one another by noticeable environmental gradients or degraded surfaces.

3. Results and discussion

3.1. Aerial photograph and orthophoto analysis of tree cover data

From the aerial photograph data, vegetation cover data has been presented in tabular and graphical form, showing areas upstream and downstream in the vicinity of dams that are

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Dam	Number of squares upstream	Number of squares downstream	Total area in km² upstream	Total area in km² downstream	Total area in km²	Photo year
Albasini	756	944	0.82	1.02	1.84	1989
	749	986	0.82	1.07	1.89	1995
Damani	287	295	0.31	0.32	0.63	1987
	391	420	0.42	0.46	0.88	1995
Mambedi	1934	2280	2.10	2.48	4.58	1995
	2663	2393	2.90	2.60	5.50	2001
Nandoni	1023	1078	1.11	1.17	2.28	1987
	1066	1121	1.16	1.22	2.38	1995
Vondo	1755	1869	1.91	2.03	3.94	1987
	2120	2345	2.30	2.55	4.85	1995

Table 2. Surface areas devoid of trees upstream and downstream of studied dams (from aerial photographs).

devoid of trees. **Table 2** summarises the calculated surface areas devoid of trees for different aerial photographs.

Table 3 shows the size of area devoid of trees derived from orthophotos both upstream and downstream of the studied dams. **Table 3** shows the total surface area devoid of trees for all studied periods on aerial photographs and orthophotos.

Table 4 shows the total surface areas devoid of tree cover that were measured using aerial photographs. The total surface areas have been expressed in square kilometres.

Table 1 shows that for the Albasini dam area on the Luvuvhu River, the surface area devoid of trees immediately upstream of the dam remained about the same = at 0.82 km² between 1989 and 1995 (**Tables 1** and **3**). The area downstream of the dam devoid of trees during the same period increased from 1.02 to 1.07 km². This is an increase in treeless area by 0.05 km² in a period of 6 years (**Tables 1** and **3**). This density increase in the treeless area is expected because of the shortage in water that would have occurred probable due to the upstream presence of the dam. The total surface area devoid of trees for the whole study area (9 km²) in 1989 was 1.84 and 1.89 km² in 1995. However, the size of treeless area upstream of the dam from 1995 to 1997 (latest studied period) increased from 0.82 to 0.84 km². This is growth of treeless area by 0.02 km². The size of the treeless area downstream of the dam from 1995 to 1997 increased from 1.07 to 1.13 km²

Dam	Number of squares upstream	Number of squares downstream	Total area in km² upstream	Total area in km² downstream	Total area in km²	Orthophoto year
Albasini	1357	1812	0.84	1.13	1.97	1997
Damani	658	873	0.42	0.55	0.96	2004
Mambedi	3397	4201	2.12	2.50	4.62	1997
Nandoni	1923	2301	1.20	1.44	2.64	2004
Vondo	3867	4125	2.42	2.58	5.00	2004

Table 3. Surface areas devoid of trees upstream and downstream of the studied dams (from orthophoto calculation).

Area	Period studied	Size of area devoid of trees in km² (upstream)	Size of area devoid of trees in km² (downstream)	Total surface area in km²
Albasini	1989-1995 (6 years)	0.00	0.05	0.05
	1995-1997 (2 years)	0.02	0.06	0.08
Total area	1989-1997 (8 years)	0.02	0.11	0.13
Damani	1987-1995 (8 years)	0.10	0.14	0.24
	1995-2004 (9 years)	0.00	0.09	0.09
Total area	1987-2004 (17 years)	0.10	0.23	0.33
Mambedi	1995-1997 (2 years)	0.02	0.02	0.04
	1997-2001(4 years)	0.78	0.10	0.88
Total area	1995-2001 (6 years)	0.80	0.12	0.92
Nandoni	1987-1995 (8 years)	0.05	0.05	0.10
	1995-2004 (9 years)	0.04	0.22	0.26
Total area	1987-2004 (17 years)	0.09	0.27	0.36
Vondo	1987-1995 (8 years)	0.39	0.52	0.91
	1995-2004 (9 years)	0.12	0.03	0.15
Total area	1987-2004 (17 years)	0.51	0.55	1.06

Table 4. Total surface area devoid of tree species of the selected dams in the Luvuvhu and Mutale river catchment.

(**Tables 1** and **2**). This is a growth by 0.06 km² (**Tables 2** and **3**). Therefore, the impact of shortage of water downstream of the dam was clearly reflected in the 1997 photographs. The total surface area devoid of trees for the study area from 1995 to 1997 was 0.08 km². Therefore, the total surface area devoid of trees for the dam study area between 1989 and 1997 grew from 1.84 to 1.97 km² (**Tables 1** and **2**) in a period of 6 years. This is an increase by 0.13 km² in 6 years (**Table 3**). From **Table 3** the total surface area devoid of trees downstream of the dam between 1989 and 1997 was bigger (0.11 km²) than upstream (0.02 km²). The increase in treeless area downstream of the dam can be explained with specific reference to alternating shortage of water downstream of the dam area. Shortage of water downstream of the dam during low-rainfall period gradually leads to a decline in riparian species richness and lower species diversity of colonising vegetation. This is because riparian species are selective when establishing themselves and they are sensitive to flooding frequency and duration [12–15]. Therefore, the diversity and function of riparian communities are impacted by river regulation [16]. Gordon and Meentemeyer [17] stated that reduced wetted perimeter of a river allows vegetation to increase by 50% along formerly inundated area. However, the colonising species are terrestrial, like *Acacia Karroo* along downstream reaches of Luvuvhu River at the Albasini dam.

For the Damani dam on the Mbwedi River, the total surface area devoid of trees upstream of the dam changed between 1987 and 1995 from 0.32 to 0.42 km² (**Tables 1** and **3**). This is an increase in area by 0.10 km² (**Table 3**). The area downstream of the dam devoid of trees between the same periods increased from 0.32 to 0.46 km². This is an increase in area by 0.14 km² in a period of 8 years. The total surface area devoid of trees for the whole dam study area (9 km²) in 1987 was 0.64 and 0.88 km² in 1995 (**Tables 1** and **3**). This is a total surface area devoid of trees of 0.24 km² in a period of 8 years (**Table 3**). However, the treeless area upstream of the dam from 1995 to 2004 (latest studied period) remained constant at 0.42 km² (**Tables 2** and **3**),

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while the treeless area downstream of the dam grew from 0.46 to 0.55 km^2 from 1995 to 2004. This is an increase in area by 0.09 km^2 (**Table 3**). Therefore, the total surface area devoid of trees grew from 0.64 to 0.97 km^2 between 1987 and 2004 within a studied dam area of 9 km^2. The total surface area devoid of trees between 1987 and 2004 grew by 0.33 km^2 within a dam area of 9 km^2. This means that the scale and magnitude of impact by upstream presence of the dam is bigger than at the Albasini dam area. This shows that downstream riparian vegetation does not receive sufficient water to support biomass production through photosynthesis. As with the Albasini dam area, the Damani dam area has also shown an increase in treeless area, with downstream reaches having bigger treeless areas.

For the Mambedi dam on the Mambedi River, the total surface area devoid of trees upstream of the dam changed between 1995 and 1997 from 2.10 to 2.12 km^2 (**Tables 1** and **2**). This is an increase in area by 0.02 km^2 (**Table 3**). The area devoid of trees immediately downstream of the dam during the same period increased from 2.48 to 2.50 km^2. This is also an increase in an area by 0.02 km^2 (**Table 3**). The total surface area devoid of trees for the whole dam study area in 1995 was 4.5 and 4.62 km^2 in 1997 (**Tables 1** and **2**). This is a total surface area of 0.04 km^2 (**Table 3**). However, the size of the treeless area upstream of the dam in the 2001 aerial photograph was 2.90 km^2 (**Table 2**). This is an increase in area from 2.12 km^2 (1997) to 2.90 km^2 (2001). This is an increase in area by 0.78 km^2 in a period of 4 years. The size of the treeless area immediately downstream of the dam increased from 2.50 km^2 (1997) to 2.60 km^2. This is an increase in area devoid of trees by 0.10 km^2 in a 4-year period. This means that the total treeless surface area for the whole dam within the studied area increased from 4.62 km^2 (1997) to 5.50 km^2 (2001), an increase of 0.88 km^2 over 4 years. However, the total surface area devoid of vegetation for the whole dam study area (9 km^2) devoid of trees grew from 4.58 km^2 (1995) to 5.50 km^2 (2001) (6-year period). This is an area of 0.92 km^2 (**Table 3**). This means that downstream riparian communities suffer water shortage during low rainfall months, and this is further worsened by the presence of the dam. This also explains why there is an increase in treeless area downstream of the dam. The size of treeless area upstream of the dam is further worsened by the fact that after the collapse of the dam wall in the year 2000, a large formerly inundated area was left dry, but was later replaced by terrestrial grass species and very few tree species. This is why the size of the treeless area in the 2001 photograph was bigger than the treeless area shown in the 1995 and 1997 aerial photographs respectively. **Plate 1** shows the area that was exposed after the failure of the Mambedi dam.

From **Plate 1** it can be seen in the background, where less water accumulates, that the area is characterised by fine thatching grass (*Hyparrhenia filipendula*) with a few unevenly scattered *Acacia ataxacantha* trees. Vegetation is still in its primary stage of succession and the stagnant water body that can be seen in the background has shown deterioration in water quality. From the photograph, it is evident that the failure of the dam reduced the aquatic environment and riparian and aquatic biota suffered from the failed water management project. The aquatic and riparian zones were colonised by terrestrial grass and woody plants. Orr [17] has stated that plant composition differs among recent and older sites as newer sites are dominated by a combination of grasses and early successional forbs. The same is true with the Mambedi dam. Again, the presence of low grass density on the banks will make the river banks more unstable and result in calving. Once this occurs, erosion of banks will increase and sedimentation will

Plate 1. The defunct Mambedi dam after the 2000 floods (December 2008).

also increase. Simon and Collison [18] have noted that if vegetation development progresses to trees banks are expected to be more stable than if banks are dominated by grass communities. This is why Russell et al. [19] have argued that without riparian vegetation, erosion and sedimentation will increase in dams. Channels that are characterised by low grass densities are more likely to lead to channel straightening [20, 21] .

For the Nandoni dam on the Luvuvhu river, the total surface area devoid of trees upstream of the dam increased between 1987 and 1995 from 1.11 to 1.16 km^2 (**Table 1**) This is an increase in area of 0.05 km^2 (**Table 3**). The area downstream of the dam devoid of vegetation during the same period increased from 1.17 to 1.22 km^2. This is also an increase of 0.05 km^2. The total surface area devoid of trees for the whole dam study area (9 km^2) was 2.28 km^2 in 1987 and 2.38 km^2 in 1995. This is a change in treeless area by 0.10 km^2, this change occurring equally upstream and downstream of the dam. This increase in treeless area both upstream and downstream of the dam might have occurred during the dry seasons accompanied by low flows due to the upstream presence of the dam. This might explain why an increase in treeless area was noted in the 1995 aerial photograph. The larger treeless area downstream of the dam between 1995 and 2004 appears to be a function of the upstream presence of the dam.

Just like with other studied dams (Albasini, Damani, Mambedi and Nandoni) there has been an increase in the size of the treeless area, especially downstream of the Vondo dam. For the Vondo dam on the Mutshindudi river, the total surface area devoid of trees upstream of the dam changed between 1987 and 1995 from 1.91 to 2.30 km^2 (**Table 1**). This is an increase in area of 0.39 km^2 in a period of 8 years (**Table 3**). The area immediately downstream of the dam devoid of trees between the same periods increased from 2.03 to 2.55 km^2; a higher increase in area of 0.52 km^2. The total surface area devoid of trees for the Vondo dam in 1987 was 3.94 and 4.85 km^2 in 1995 (**Table 1**). This means that from 1987 to 1995 the total surface area devoid of tree species grew by 0.91 km^2 within an area of 9 km^2.

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It can therefore be concluded that there is also insufficient water available for downstream vegetation during dry periods. This led to the disappearance of trees along downstream reaches of all studied dams, including Vondo dam. The area upstream of the dam increased from 2.30 km^2 (1995) to 2.42 km^2 in 2004 (**Table 2**). This is an increase of 0.12 km^2. However, the area downstream of the dam only increased from 2.55 to 2.58 km^2. This is increase of 0.03 km^2. This means that the total surface area between 1995 and 2004 increased from 4.85 to 5.00 km^2 (**Tables 1** and **2**). This is a total surface area of 0.15 km^2 (**Table 3**). Therefore, the total surface area devoid of trees in a 17 year period (1987–2004) increased from 3.94 to 5.00 km^2. This is the total surface area of 1.06 km^2 (**Table 3**).

Progressive increase in treeless area shows that the growing conditions might have been altered by reduced river discharge and alternating wet-dry periods. This means that the growing conditions that existed before or during the construction of the Vondo dam, differed from those existed after the construction. Therefore, colonisation and primary plant succession took place under different conditions that existed before the construction of the dam. Doyle et al. [22] also argued that succession of plant communities in the formerly inundated area will occur under very different conditions than those existed at the time of dam construction. This is why the succession conditions downstream of the studied dam areas favoured the proliferation of terrestrial species like *Acacia ataxacantha and Acacia Karroo*. An interesting observation by Vale et al. [23] was that reduction in moisture of the soil leads to reduction in water-related species such as *H. gralipes, I. laurina, A. edulis* and *I. vere.* This explains the presence of terrestrial tree species such *Acacia Karoo* in formally inundated downstream environments. Caskey [24] also noted that diversion-induced flow alteration in the Rocky Mountains of the Colorado led to the reduction in the frequency of hydrophytic wetland species and the proliferation of non-hydrophytic upland species. **Figure 3** shows the total surface areas of studied dams devoid of trees calculated from aerial photographs and orthophotos of different years as depicted in **Table 3**.

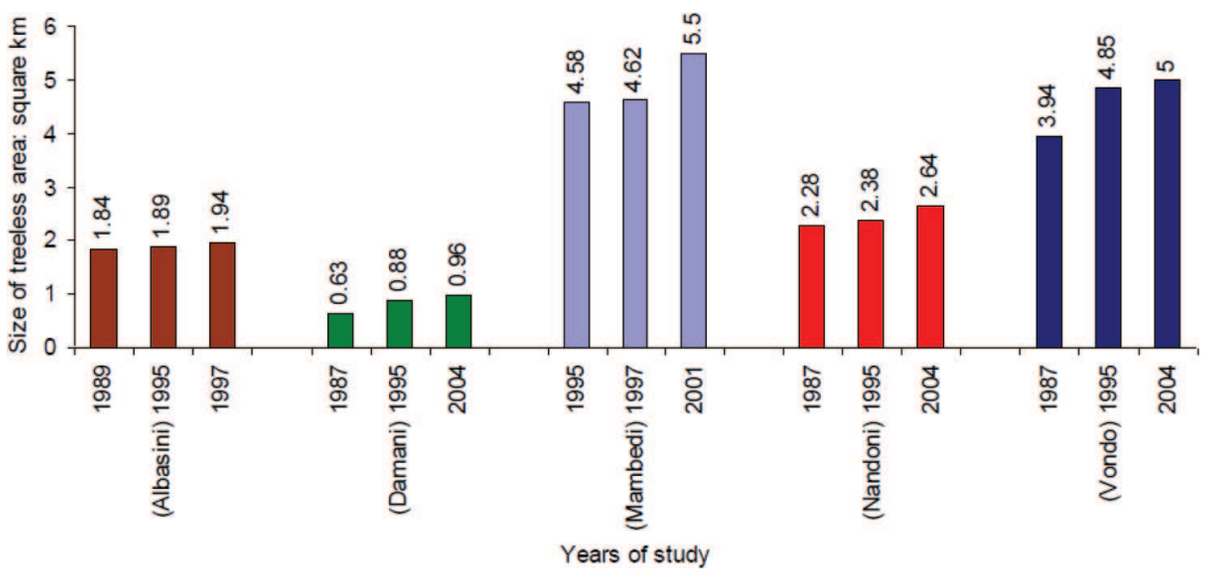

Figure 3. Total surface areas upstream and downstream of dams devoid of trees.

3.2. Tree cover data from aerial photographs and orthophotos

The degree of tree cover for all studied dams has been described based on the method of Dansereau [11] on vegetation description as highlighted by Kent and Coker [7]. **Table 5** shows the latest state of tree cover as studied from the latest aerial photographs of the study areas using Dansereau's method.

Tree density is a function of rainfall or moisture availability. Therefore, a cut in water downstream of the Luvuvhu/ Mutale dams, due to the upstream presence of the dams, has led to a decline in tree density (**Table 5**). Jones et al. [25] have also noted that tree stands decreased along the Colorado and Gila River systems of USA due to the existence of dams.

Study area	1st photograph	2nd photograph	3rd photograph
Albasini	1989	1995	1997
	Discontinuous (i) both upstream and downstream	Discontinuous (i) both upstream and downstream	Discontinuous (i) both upstream and downstream (signs of patchiness evident downstream)
Damani	1987	1995	2004
	Continuous (i) downstream (Before the existence of the dam in 1991) Continuous (c) upstream (before the existence of the dam in 1991)	Discontinuous (i) downstream with signs of patchiness Continuous (c) upstream. Dam present.	Discontinuous (i) downstream and close to barren Continuous (c) upstream
Mambedi	1995	1997	2001
	Discontinuous (i) downstream with signs of patchiness (barren) Discontinuous (i) upstream	Discontinuous (i) downstream with signs of patchiness (barren) Discontinuous (i) upstream	Discontinuous (i) downstream with signs of patchiness (barren) (after wall failure) Discontinuous (i) downstream with signs of patchiness (barren) (after wall failure)
Nandoni	1987	1995	2004
	Continuous (c) over the entire area before dam was constructed	Continuous (c) over the entire area but shows signs of discontinuity because of the existence of the small Mutoti dam and human settlements	Discontinuous (i) over the entire area because of the existence of the small agricultural lands and human settlements
Vondo	1987	1995	2004
	Tufts and groups (p) downstream and upstream of the dam because of tea plantation fields	Tufts and groups (p) downstream and upstream of the dam because of tea plantation fields	Tufts and groups (p) downstream and upstream of the dam because of tea plantation fields

Table 5. Latest state of tree cover for the five selected Luvuvhu/Mutale dams.

http://dx.doi.org/10.5772/intechopen.78329

3.3. Field data from the selected dams in the Luvuvhu and Mutale river catchment

3.3.1. Tree density

Tree density data was collected from the five dams studied through field survey. The mean distances for tree species from the Luvuvhu/Mutale dams were measured and the results are shown in **Table 6** and **Figure 3**. Tree densities upstream and downstream of the dams studied.

From **Figure 4** Vondo shows slightly higher upstream density and much lower downstream density. Vondo shows lower downstream density than all studied dam areas. Downstream of Vondo dam area, is less dense (10.11 m^2) than in all studied dam areas while Albasini dam area is denser.

However, the Vondo dam area is characterised by commercial agriculture and human settlement along the Mutshindudi River. Therefore, the extent of the impact of the dam downstream is complicated by the existence of settlements and intense commercial farming (tea plantations). The field data and photo data do not correspond in all cases but this happen to agree in this particular case because of the human settlements and tea plantations. For example, Kellog and Zhu [26] noted that during the construction of the Three Gorges Dam (China) clearing of vegetation for agriculture the average width of the upstream waterway increased from 0.6 to 1.6 km. This shows how dams negatively impact on their immediate environments. The same is true with the area in the vicinity of the Vondo dam. Therefore, the lower tree density downstream of the Vondo dam corresponds with the size of the treeless area (1.06 km^2) calculated from remotely sensed images. Results in **Table 6** and **Figure 3** also show that upstream tree

Dam	Mean distance (*m*) to nearest *n* individual species upstream	Mean distance (*m*) to nearest *n* individual species downstream	Tree density upstream in m^2	Tree density downstream in m^2	Tree species name
Albasini	8.29	8.32	5.86	5.88	Sweet thorn (*Acacia karroo*)
Damani	5.98	9.65	4.22	6.82	Flame thorn (*Acacia ataxacantha*)
Mambedi	10.04	12.06	7.09	8.52	Flame thorn (*Acacia ataxacantha*)
Nandoni	6.5	9.3	4.59	6.57	Flame thorn (*Acacia ataxacantha*)
Vondo	7.7	14.3	5.44	10.11	Flame thorn (*Acacia ataxacantha*)

Table 6. Tree density upstream and downstream of the dams studied (December 2009).

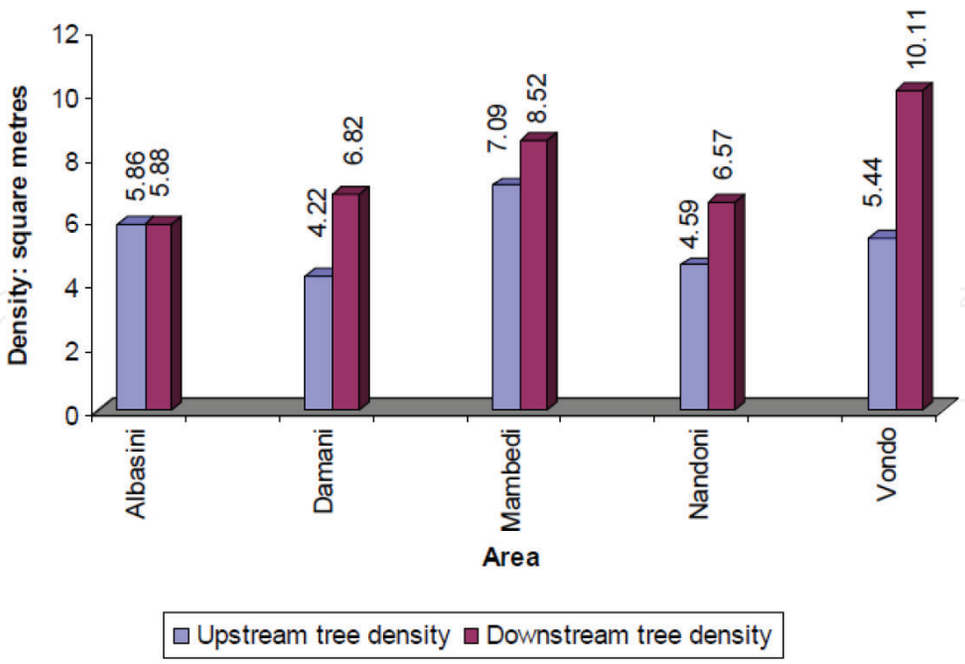

Figure 4. Tree densities downstream and upstream of the dams.

density is highest at Damani dam (4.22m^2) on the Mbwedi River and lowest at Mambedi dam (7.09m^2) on the Mambedi River. Downstream tree density is highest on the Albasini dam and lowest in all other dams. Downstream tree density is highest on the Albasini dam (5.88 m^2) and lowest on the Vondo dam (10.11m^2). Tree density upstream of Nandoni dam is higher (4.59 m^2) than downstream of the dam (6.57m^2). Thus, the growth in treeless area downstream of all studied dams occurs as a result of low flows which are available for riparian irrigation. This is caused by the upstream presence of the dams. This, according to Lees et al. [27] and Sutherland et al. [28], occurs because construction of dams leads to fragmentation and degradation of riparian zones which also leads to loss of ephemeral habitats.

The magnitude of degradation is a function of resilience and fragility of the area which is controlled by soil type, size of the dam, age of dam, size of degraded area during the construction of the dam, species diversity, succession stages, climatic variability, energy pools and routes and soil instability [29]. Albasini dam area has a smallest difference between the downstream (5.88 m^2) and upstream (5.86 m^2) tree density. This is a function of the age of the dam: vegetation, predominantly terrestrial, having had sufficient time to regenerate after the construction of the dam in 1952. Vale et al. [30] have noted that dam impact stabilises a few years after impoundment but becomes intense immediately after dam construction. This explains the smallest difference between downstream and upstream areas. However, Vondo dam area has lower tree density because it is located in a more humid area characterised by high rainfall and sensitive soils. Soils of the area are therefore dystrophic (nutrient-poor). This explains why the area became sensitive to water shortage downstream of the dam. Vegetation that thrived well under humid conditions suffered when river discharge was reduced downstream of the

http://dx.doi.org/10.5772/intechopen.78329

Vondo dam on the Mutshindudi river. This is because conditions became too dry for riparian communities resulting in loss of diversity. Graf [31] similarly argued that regulated reaches are less likely to support extensive ecosystem components requiring a dry period of summer, and the species diversity will be lower.

4. Conclusion

In all the five dams studied, downstream treeless area has increased progressively over the years. In all cases, aerial and orthophotos showed increasing discontinuity in downstream tree cover. Treeless area is bigger downstream than upstream in all cases (except the Mambedi dam, which failed in the year 2000). There is lower species richness downstream than upstream (again, except in the case of the failed Mambedi dam). In all the downstream riparian zones, the predominant vegetation is obligate terrestrial species. Downstream vegetation is less dense than previously and less dense than upstream, although in the case of the oldest dam (Albasini), the difference is small, as the terrestrial vegetation downstream has had more time to recover. These effects are ascribed to the probable presence of the dams causing reduced downstream flows during dry seasons.

From the above summary of the findings of all five dams studied, it can be concluded that any modification of river flow through damming alters flow characteristics and impacts negatively on nutrient cycling of lotic environments. This is accompanied by low downstream species diversity. All dams are characterised by low surface or runoff downstream. Changes in river flow due to damming have led to the replacement of riparian vegetation with terrestrial vegetation or alien plant species in other dams. All downstream sections of the studied dams are characterised by terrestrial vegetation in formerly inundated riparian zones. Total annual rainfall does not guarantee the regeneration of disturbed areas since regeneration depends on many combined factors such as size of dams, size of degraded area during dam construction, natural species diversity, successional stages, climatic variability, energy pools and routes and soil instability. The resilience and fragility of disturbed areas depend on the combination of some of these factors.

Acknowledgements

We are grateful to the Department of Research and Innovation, University of Venda for the provision of research funds (I369) that enabled us to complete the research.

Conflict of interest

The authors declare no conflict of interest.

Author details

John M. Mokgoebo[1]*, Tibangayuka A. Kabanda[2] and Jabulani R. Gumbo[3]

*Address all correspondence to: matjutla.mokgoebo@univen.ac.za

1 Department of Geography and Geo-Information Sciences, University of Venda, Thohoyandou, South Africa

2 Department of Geography and Environmental Science, North-West University, Mmabatho, South Africa

3 Department of Hydrology and Water Resources, University of Venda, Thohoyandou, South Africa

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