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Alien Invasive Aquatic Plant Species in Botswana: Historical Perspective and Management

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Abstract: Aquatic ecosystems in Botswana have been under threat by the aquatic alien invasive plant species *viz*., salvinia *Salvinia molesta* Mitchell, water lettuce *Pistia stratiotes* L., and water hyacinth *Eichhornia crassipes* (Mart.) Solms-Laub. While salvinia has been termed the major threat to the Botswana wetlands, water lettuce and water hyacinth are considered to be of minor importance. This review presents the species biology, distribution, historical spread, negative impacts, control achieved right from their discovery in the country by referring to their control and management in the world.

Having infested the Kwando-Linyanti-Chobe Rivers in the 1970s, salvinia was initially tried by the use of herbicides, paraquat and glyphosate, between 1972 and 1976. With the discovery of the host specific biological control weevil *Cyrtobagous salviniae* Calder and Sands in 1981, the weevil was introduced by Namibians on Kwando and Chobe Rivers in 1983 and by Botswana in 1986 in the Okavango Delta. While the control was slowly establishing in Kwando-Linyanti-Chobe Rivers, it became apparent that lakes and perennial swamps within and outside Moremi Game Reserve of the Okavango Delta were infested with salvinia from 1992 onwards. With continuous and sustained liberation of the weevil in the Kwando-Linyanti-Chobe Rivers and in the Okavango Delta between 1999 and 2000, salvinia control was achieved by 2003, and since then the weevil constantly keeps the weed at low levels. The success is mainly due to sustainable monitoring through the application of physical and biological control methods. However, salvinia is still threatening the Okavango Delta due to factors such as tourism activities, boat navigation fishing and transporttion by wild animals.

The first occurrence of water lettuce was recorded on Kwando and Chobe Rivers in 1986. Its biocontrol weevil *Neohydronomous affinis* Hustache was released in the year 1987. The weevil became extinct in Selinda Canal and Zibadianja Lake on Kwando River due to dry and wet events for over 10 years and the weed had been under control biologically on Chobe River. Having surface covered the Selinda and a part of the Zibadianja in high flood and rainfall in 1999/2000 season, research was undertaken to contain water lettuce, which led to its eradication by 2005. Regular physical removal of the water lettuce prior to fruit maturity is an effective method of control or eradicating the weed in seasonal water bodies.

The Limpopo Basin (shared by Botswana, South Africa, Zimbabwe and Mozambique) has become vulnerable to water hyacinth infestation. Water hyacinth infested the trans-boundary Limpopo River in 2010 sourced from Hartbeesport Dam on Crocodile River in South Africa. Botswana and South Africa have been consulting each other to implement integrated control of the weed jointly in the Limpopo River. Water hyacinth could be a continuous threat to the dams and the rivers in the Limpopo basin if its control is not taken seriously.

These three species are found growing in Botswana in a range of pH between 4.5 and 10.3 and in the range of conductivities between 20 and 580 $\mu S\ cm^{-1}$. Range of soluble nitrates, phosphates and potassium in the habitats of salvinia infestations were 0.02 to 1.5, 0.01 to 1.78 and 0.3 to 6.92 $mg\ L^{-1}$ respectively. Water lettuce infestation in the seasonal Selinda Canal had a maximum of 4.7 $mg\ L^{-1}$ nitrates, 2.8 $mg\ L^{-1}$ phosphates and 7.9 $mg\ L^{-1}$ potassium. Nevertheless, these three nutrients were in the range of 0.41 to 9.56 $mg\ L^{-1}$, 0.2 to 2.9 $mg\ L^{-1}$, and 7.7 to 11.53 $mg\ L^{-1}$ respectively in the Limpopo River where water hyacinth infestations were observed. These nutrients were considerably high during decomposition phase of biological control of weeds.

The Government of Botswana "regulates the movement and importation of boats and aquatic apparatus, to prevent the importation

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and spread of aquatic weeds both within and from the neighboring countries" by "Aquatic Weed (Control) Act" implemented in 1986. These measures, combined with communities, conservation groups, NGOs and public awareness campaigns, have highlighted the gravity of aquatic weeds spreading into wetlands, dams and other water bodies. In conclusion, the Government of Botswana is committed and supportive through the Department of Water Affairs in protecting the wetlands of the country efficiently and prudently.

Keywords: Botswana, Invasive weeds, Management, Salvinia, Water lettuce, Water hyacinth.

1. INTRODUCTION

The top five most damaging alien invasive plant species to the aquatic systems, generally termed the "Big Bad Five" are of South American origin [1]. They are: water hyacinth *(Eichhornia crassipes* (Martius) Solms-Laubach), Kariba weed or salvinia (*Salvinia molesta* Mitchell), water lettuce (*Pistia stratiotes* L.), parraot's feather (*Myriophyllum aquaticum* (Vell.) Verdc.), and red water fern (*Azolla filiculoides* Lam.). Of these five species, salvinia, water lettuce and water hyacinth are part of the aquatic systems in Botswana. As a major threat, salvinia has been common in the lower Okavango Delta on the northwest and Kwando-Linyanti-Chobe River systems bordering Botswana and Namibia on the northeast of the country. These areas are rich in nutrients with abundance of aquatic habitats. Water lettuce was found in Kwando until its eradication in 2005 and is still present in the Chobe River. Water hyacinth was observed in 2010 in the transboundary Limpopo River between the Republic of Botswana and the Republic of South Africa. Two factors mainly contribute to the weed invasions: the "lack of co-evolved natural enemies in their introduced range and the presence of nitrate and phosphate rich waters associated with eutrophication" in the wide range of aquatic habitats [2]. The three "biological pollutants" cause extensive socio-economic and water resource use management problems in Botswana riverine and wetland systems. Ornamental pond industries and aquarium trade have been singled out as a strong contributing pathway to the introduction and spread of aquatic invasive plants [3, 4].

2. WEED PROBLEMS IN AFRICA AND ELSEWHERE

Invasive weeds cause a variety of problems in Africa that are broadly similar to those caused by aquatic weeds elsewhere in the world. In Africa, aquatic weeds interfere with water flow in rivers, canals and drains, thereby imperiling irrigation schemes and slowing drainage of water from floodplains; impede boat navigation, recreation and fishing; suppress indigenous vegetation by overgrowth and affects the light climate in the water; threaten hydroelectric power plants; increase water loss through evapotranspiration, and entrap sediment, thus decreasing the capacity of the reservoir for water resources [5, 6]. Thick spread of weed mats impacts water quality by decreasing dissolved oxygen (DO) and pH, increasing CO_2 and H_2S concentrations thereby affecting nutrient balance, especially those of PO_4, and NO_3 [6, 7].

Dense weed infestations harbor vectors such as the "species of mosquitoes that transmit encephalitis, dengue fever, malaria, cholera" and the spread of the snail *Biomaphalaria boissyi*, an intermediate vector of bilharzia or schistosomiasis [8]. In the Southeast Asia region, Mansonia mosquitoes are the main vectors involved in the transmission of lymphatic fillariasis caused by *Brugia malayi,* which breeds mostly on water hyacinth [9, 10].

There are some specific negative impacts related to the weeds. Stable mats of salvinia are associated and invaded by other plants such as grasses and sedges, which colonize to form floating communities (or sudds) that may float freely, thus acting as transporter of other species [11]. Although, water lettuce is not one of the world's most important weeds, the plant has been found to affect wetlands in a localized manner in several parts of Africa [12]. Water hyacinth has enormous social, economic and environmental impacts, earning this plant the title "world's No. 1 aquatic weed", challenging the ecological stability of freshwater water bodies in the world [13, 14], "out-competing all native species" and threatening the "fisheries" more than the other weeds [6, 14]. Water hyacinth impacts on the poverty-stricken communities in rural Africa and India" are yet to be fully reported [15]. Water hyacinth causes significant increase in water loss due to transpiration compared to other two weeds. However, all the negative impacts of weeds found in literature are not associated with every country in common. Therefore, the impacts are to be identified in relation to country's water bodies' use pertaining to their socio-economic benefits and conditions.

3. OBJECTIVE

The wetlands of Botswana and its waterways have demanded the Alien Invasive Species (AIS) distribution, control, and management. Historical knowledge is required for improving the AIS control strategy and management in different habitats by choosing the suitable control measures. This review illustrates AIS management practices, ecosystem approaches, adaptive management, stakeholder involvement and the progress of control made over three decades in the country.

Control technologies (*e.g*., physical, chemical, and biological) managing the species are discussed in relation to Botswana by briefly referring to other countries. Also, the "Aquatic Weeds (Control) Act of Botswana" implemented in 1986 concerning the AIS movement within and from outside the country and "Boat Regulations" are briefly presented.

4. *SALVINIA MOLESTA* MITCHELL - SALVINIACEAE

4.1. Distribution in the World

Salvinia molesta is a free-floating, mat forming water fern of tropical and subtropical distribution worldwide. Salvinia is "native to southeastern Brazil, in a subtropical zone (between latitudes 24º 05' S and 32º 05' E) extending up to 200 km inland to an elevation of 0 to 500 m" [16]. It has become a serious nuisance in over 20 countries [17, 18]. *Salvinia molesta* has been established with its host specific biological control weevil *Cyrtobagous salviniae* Calder and Sands in the South and North Americas [19], New Zealand [20], Australia [21], Fiji [22], the Philippines [23], India [24], Indonesia, Malaysia, Singapore, and Papua New Guinea [25], Cuba, Trinidad, Guyana, Columbia [18], Malaysia [26] and in southern Kalimantan (formerly Borneo) [32]. In Africa, it has been found in Botswana, the Ivory Coast Republic [27], Ghana, Zambia, Kenya [28], Namibia [29, 30], and in South Africa [31]. Historically notable and threatened infestations have occurred in the "Sepik River" [33] and in the **"**Zambezi River, Lake Naivasha, Kariba Lake, and the Chobe River" in Africa [11].

Salvinia was not known to occur naturally in Brazil although specimens collected in Botanical Gardens of Rio de Janeiro in 1940 are in the Garden's Herbarium. Nothing was known about salvinia until it was discovered apparently for the first time in Sri Lanka in 1939. The dispatch of salvinia plant material was traced via Germany and Kalkota in India to the University of Columbo in Sri Lanka for use in "Botanical Studies" in 1939 [34]. What probably remains a secret or unknown is how it came to the African continent.

4.2. Biology and Ecology

Taxonomic position: Division: Pteridophyta, Class: Filicopsida, Order: Hydropteridales, Family: Salviniaceae, Genus: *Salvinia* Séguier, Species: *Salvinia molesta* Mitchell [35]. *Salvinia molesta* was named in honour of Antonio Maria Salvini (Italian Scientist, 1633-1729), University of Florence. The specific epithet '*molesta*' originates from the Latin '*molestus'* means "troublesome," "annoying," referrin to molesting the water environment by its weed character [36]. *Salvinia molesta* is widely called "salvinia"; but it is also called "Kariba weed, water fern, or African pyle in Africa; giant azolla or Australian azolla in the Philippines; and giant salvinia, water spangles or floating fern in the United States of America" [11]. In native "Setswana" language of Botswana, it is called "mochimbamo".

Fig. (1a). *Salvinia molesta* apically joined hairs resembling "egg-beater" or "cage" and larvae of *Cyrtobagous salviniae* (Photo by Kurugundla 2010).

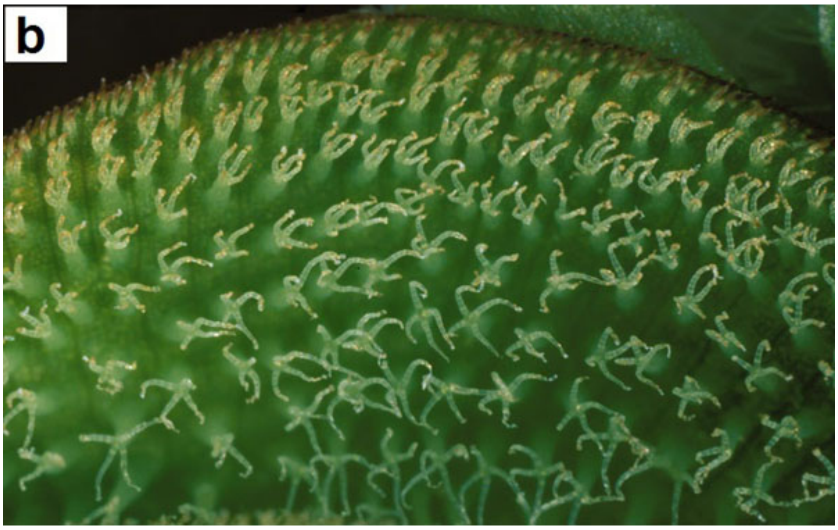

Fig. (1b). *Salvinia minima* - the hairs are separated at the tips (photo by T. Center).

Fig. (1c). Tertiary growth form showing ramets and sporocarps (Photo by Kurugundla 2010).

The monogeneric family Salviniaceae has only genus *Salvinia* and represents 10 -12 species [37]. Of these species, the *S. auriculata* complex comprises *S. auriculata* Aublet, *S. biloba* Raddi, *S. herzogii* de la Sota, and *S. molesta* Mitchell, which are closely related to each other. "Species within this complex are characterized by the presence of divided but apically joined 'basket' hairs on the abaxial (upper) surface, which produce an "egg-beater" or "cage" (Fig. **1a**) like appearance [16]. These hairs are hydrophobic, that is, they repel water. *Salvinia molesta* was separated from other species of the *S. auriculata* complex "based on the arrangement of sporangia, the shape of sporocarps" [38], and "by the pattern of leaf venation" [16]. In the other species such as *S. minima* Baker, "the leaf hairs are simple and unbranched" (Fig. **1b**). Among the species of *Salvinia, Salvinia molesta* is a notorious weed in its introduced areas.

Description: All species of *Salvinia* consist of horizontal rhizomes bearing short stalked leaves in whorls of three. Two opposite leaves are floating and green while the third one is submersed and highly divided to function as "roots" [39]. Aerenchyma tissue in the stems and leaves facilitates buoyancy [40]. Floating leaves are generally ovate to cordate with distinct midribs. Submersed leaves ("roots") have heterosporous sporangia (Fig. **1c**): megasporangia and microsporangia occur on the same plant but in separate sporocarps. The species of *S. auriculata* complex bear sterile sporangia while *S. oblongifolia* Martius, and *S. nymphellula* Desv., bear fertile sporangia. The node, its two leaves, axillary buds (lateral buds) and "roots" function as an independent module called a "'ramet". A single ramet or a cluster of joined ramets forms a plant. The apical and axillary buds give rise to the new branches at each node. *Salvinia molesta* exhibits "three phenotypic growth forms" mainly depending on habitat, crowding, and nutrient availability [28, 41].

i. The "primary invading stage" occurs as isolated plants producing small, oval leaves, from 2 to 15 mm wide, that lie flat upon the surface of the water. This form of growth may also be observed in plants recovering from damage or in uncrowded conditions in shade or nutrient-rich waters [42].
ii. The "secondary colonizing stage" of plants is evident in open water. Stem internodes are longer, leaves are larger, slightly keeled but do not overlap and the lower leaf surface is in contact with the water. Sizes of the leaves may vary from 20 to 50 mm in diameter

iii. The “tertiary-mat stage” occurs under crowded conditions typically associated with mature and fully grown mats. This form has relatively short internodes. The leaves are large (up to 60 mm in diameter), heart shaped or oblong, and deeply keeled. As crowding increases, the leaves are pushed upward to become erect and packed into mats.

Growth and reproduction: *Salvinia molesta* is pentaploid explaining irregularities that occur during meiosis, which prevent normal spore formation, and is functionally sterile [43]. Each node bears a series of up to three axillary buds that develop successively under normal growing conditions [41, 44], and up to six in response to damage and under stress conditions [45]. Salvinia growth is apically dominant and under optimal growth conditions the plant assumes zigzag appearance by the activity of apical and axillary buds producing new branches successively at each node [44]. New plants form when older plants break apart due to senescence or damage [46].

Uses: The plant can be “used as a compost and mulch and as a supplement to fodder for livestock” [17]. Since the plant has up to 90% water content, use of the plant for “treating sewage effluent” [47], “papermaking”, and the generation of “biogass” [33] is not cost effective.

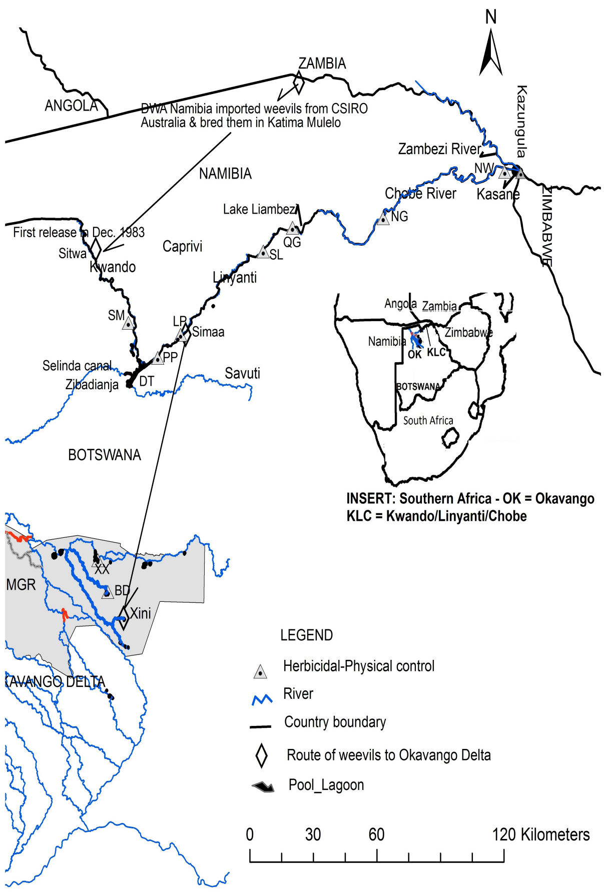

Fig. (2). Kwando-Linyanti-Chobe River systems showing the areas of herbicidal, physical and biological control applications between 1972 and 1976. The first releases of the weevil, *Cyrtobagous salviniae* at Sitwa on Kwando River was made in Caprivi-Namibia. The route of *C. salviniae* from Katima Mulilo→Sitwa on Kwando→Simaa Lagoon on Linyanti→Lake Xini in the Okavango Delta in 1986 is seen by arrow illustration. Kwando-Linyanti-Chobe: SM = Shummamorei (Physical), DT = Dumatau (Physical), PP = Ponpon (Herbicidal), LP = Lupala Island (Physical), SL = Shaile (Herbicidal), QG = Quega (Herbicidal), NG = Ngoma (Biological), NW = Nungwe (Herbicidal), Kazungula = *Salvinia molesta* first discovery. MGR = Moremi Game Reserve in the Okavango Delta: BD = Bodumatau, XX = Xaxanaka.

4.3. Historical Spread in Botswana

The earliest collection of salvinia species was made in 1948 at Kazungula on Zambezi River near Kasane (Table **1**, Fig. **2**) in the eastern Caprivi [48] bordering Botswana and Namibia. First new outbreaks were discovered in Chobe River in the 1970s from the Zambezi River via flood plains [49]. By the end of 1972, salvinia had spread throughout the Kwando-Linyanti-Chobe River system on the border between Botswana and Namibia [27]. It was expected that the weed could go along the Selinda Canal from Kwando River (Fig. **2**) as the canal is connected to the adjoining Okavango Delta and fortunately it did not happen as the canal became seasonal from 1988 until 2010.

Table 1. First discovery of alien invasive species in various wetland and riverine systems in Botswana.

Salvinia *Salvinia molesta* Mitchell
Chobe River at Kazungula: 1948
Kwando-Linyanti-Chobe Rivers: 1971
Okavango Delta: Xini - July 1986; Bodumatau - July 1988; Gomoti - 1990; Abaqao/Mogohelo, - August 1992; Xaxanaka on Maunachira - July 1992; Khwai - 1992; Khwai at Mababe -April 2000; Dombo 1995; Santantadibe at Ditshipi - November 2002 and at Sandibe - 2003; Mboroga feeder channel and Maunachira Hippo pool - January 2007; Gadikwe and Xugana Lagoon - March 2008; Boro River - June 2010; Thamalakane - December 2012
Water Lettuce *Pistia stratiotes* L.
Absent in the Okavango Delta. First discovered in Chobe River in 1986 and after three months in Selinda Canal and Zibadianja Lagoon of Kwando River
Water hyacinth *Eichhornia crassipes* (Martius) Solms-Laubach
Absent in the Okavango Delta, Kwando-Linyanti-Chobe Rivers. However, found as an ornamental plant in few homes of Kasane village on 27 March 2002 and in Maun village close to the Okavango Delta in January 2016, confiscated the weed and destroyed. Trans-boundary Limpopo River: First reported in May 2010 and its source of infestation is from Hartbeesport Dam and Crocodile River in South Africa.

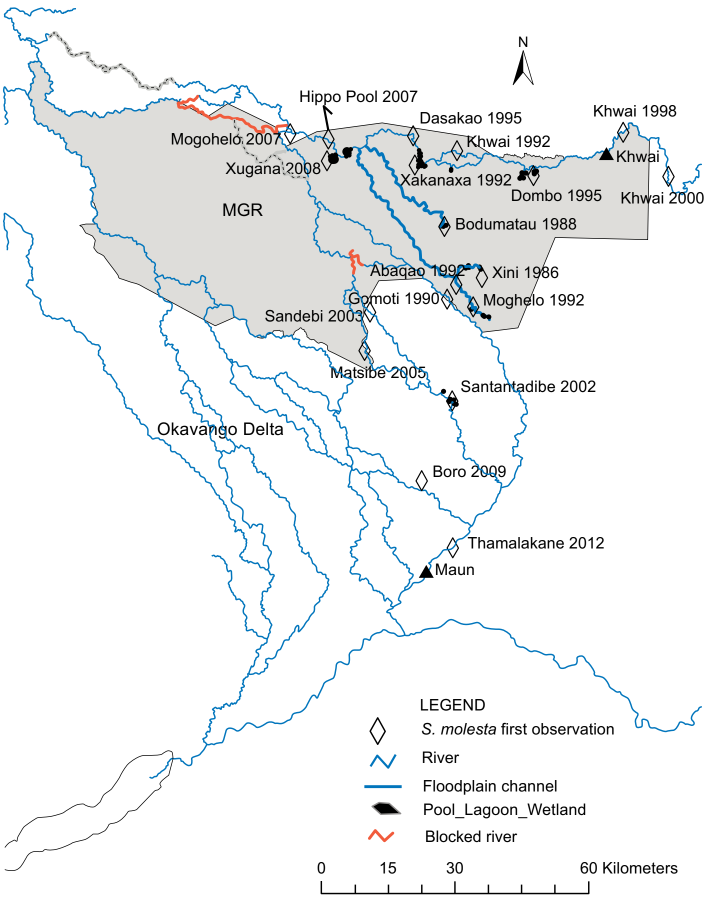

Fig. (3). First discoveries of *Salvinia molesta* in Moremi Game Reserve (MGR) and outside MGR of the Okavango Delta.

Salvinia was first discovered in the Okavango Delta on 14 July 1986 in Xini Lagoon (25 km^2) (Fig. **3** and Fig. **4a**) and two years later in Bodumatau chain of pools with associated wetlands (2 km^2) [50]. With these discoveries salvinia has threatened the entire Okavango Delta and subsequently documented by the Department of Water Affairs (DWA), Botswana in several riverine channels confined to Moremi Game Reserve (MGR) and few areas outside the Reserve. By 1990, dense mats were observed along the fringes of vegetation in Gomoti River for a length 40 km and by the end of 1992, it was carried by floods to the adjacent Abaqao and Mogogelo Rivers. In about the same year 30% of the Xakanaxa Lagoon on its southern part, on Maunachira River was occupied by salvinia. By 2000, the weed extended further along the entire length of the 60 km Khwai River. A notable observation in 1996 was the 80% coverage of the weed in Dombo Lake, an important tourist spot in MGR.

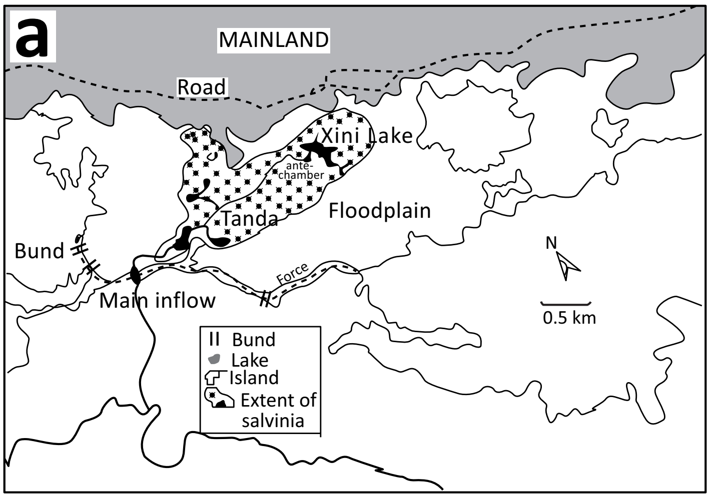

Fig. (4a). Xini area in Moremi Game Reserve of the Okavango Delta showing the topography and the extent of the infestation of *Salvinia molesta* in 1986 (Source: [50]).

Fig. (4b). "Salvinia weevil" at work (Photo by Kurugundla).

Several early salvinia discoveries were close to the safari lodges in Moremi Game Reserve including following important tourist lodges: Camp Okuti, Moremi Safaris, Desert and Delta in Xakanaxa, Khwai River Lodge on Khwai River and Sandibe Camp on Santantadibe River. One can speculate, therefore, that the plants could have been spread by tourist movement and boat navigation. Despite effective physical and biological control methods, which have been in place, further spread of the weed were observed with 90% cover in five pools on Santantadibe River and the riverine wetlands in early 2002 and in the upstream Santantadibe Rriver covering from 30% to 60% of surface water area in 2003. In 2007 sporadic mats of salvinia were noticed in the origin of Mboroga River, and in one of the hippo pools of Maunachira River. A few mats of salvinia in a hippo pool with its associated deeper floodplains of Boro River were observed in 2009 and slowly increased in surface coverage by 90% in 2011 in spite of regular manual removal. The weed was brought to the site by hippopotamus in the high flood. Salvinia was observed in December 2012 in Thamalakane River that passes through the highly populated Maun Village and its spread was augmented by fishing (Fig. **3**) [51].

4.4. Negative Impacts in Botswana

The Socio-economic impacts of salvinia in Botswana are mostly related to tourism, boat navigation, community fishing, hydrology, water supply, and decomposition, implying that it negatively impacts recreational and hydrological activities as well as the environment. Thick surface coverage of salvinia in tourist spots of Dombo Lagoon, Oyi wetlands, Xakanaxa Lagoon, Xini Lake and other areas of the Okavango Delta affected tourism activities in 1986, 1992, 1998 and 2010 (Fig. **3**). The infestation posed a potential threat to water supply, the fishing industry, tourist activities and photographic safari companies in the Chobe River [50] and between 2010 and 2013 in Boro and Thamalakane Rivers. Stable mats of salvinia in association with grasses form sudds in small narrow streams affecting the normal flows in the Delta. Similar threats of salvinia to aquatic systems have been described [11]. There are about more than 22 aquatic species that are associated with salvinia in Botswana. They include: *Polygonum* spp.; water primrose *Ludwigia stolonifera* (Guill. & Perr.) Raven; grasses *Leersia hexandra* Swartz, *Panicum repens* L., *Vossia cuspidata* (Roxb.) Griff.; sedges *Cyperus papyrus* L., *C. articulata* L.; duck weeds *Lemna* spp. and *Spirodela* spp.; water ferns *Azolla pinnata* R.Br. and *Marsilea* spp. and insectivorous plants *Utricularia gibba* L., *U. stellaris* L.f. and *U. foliosa* L. About 40 plant species that colonized with salvinia have been documented in Lake Kariba, Central Africa [52]. These "deceptive islands have caused a number of “livestock deaths” by drowning in deep water [53]. Few incidents of this nature were observed with wild animals such as Impala and Kudu in the Okavango Delta.

Complete surface coverage of salvinia out-competed the growth of plant species *viz*., *L. stolonifera*, *L. hexandra,Marsilea* spp. and *U. gibba, U. stellaris, U. foliosa* in Dombo Lagoon in 1998, Ditshipi pools in 2005 and Xini Lake in 2010 in the Okavango Delta. These plants were found re-established as soon as the salvinia control was achieved. The areas recorded less dissolved O_2 high turbidity and high nutrient accumulations during its biocontrol process using *C. salviniae* as observed in Xini Lake (Table **2**) [54]. Except total phosphates, the nutrients declined significantly after salvinia control as a result of free exchange of ions through various transport mechanisms (*e.g*., bioturbation, water currents and diffusion) and absorption of nutrients by the re-establishment of indigenous vegetation in the Lake. The immobilization of total phosphates even after control reflected that soluble reactive phosphorous (SRP) fluxes were very low, indicating that phosphorus might be a limiting factor [55]. About 111.4 tons of dry salvinia biomass were decomposed (Table **6**) as a consequence of biological control in the Xini Lake resulting in eutrophication with the increase of nutrients for about 5 months (Table **2**). Due to unfavorable conditions, fish did not move to the Lake from its upstream pool where the fish was common and abundant. As the plants die either by natural means or by the consequence of biocontrol agents, organic debris accumulate at the bottom of the water column and can threaten fish and increase soluble nutrients [56].

Table 2. Physical-chemical characteristics of water with *Salvinia molesta* infestation and after its successful control in Xini Lake/Lagoon in 2009. Source: [54].

Condition	pH	Turbidity NTU	EC µS cm^{-1}	TDS mg L^{-1}	DO mg L^{-1}	HCO_3 mg L^{-1}	NO_3-N mg L^{-1}	PO_4-P mg L^{-1}	K mg L^{-1}	Na mg L^{-1}	Ca mg L^{-1}	Mg mg L^{-1}
S. molesta Infestation	7.2 ±0.1	16.9 ±9.3	233.1 ±27.3	212.4 ±22.9	0.4 ±0.3	223.5 ±26.4	2.4 ±0.2	2.9 ±0.3	12.3 ±0.4	22.8 ±0.4	14.3 ±0.7	5.4 ±0.5
After Control	7.4 ±0.2	1.8 ±0.3	121.3 ±22.9	100.8 ±5.6	4.8 ±0.2	81.3 ±6.1	0.5 ±0.1	2.3 ±0.4	1.5 ±0.3	5.1 ±0.2	15.9 ±1.7	00.0

4.5. Factors Affecting Growth

Temperature: The optimum temperature for salvinia growth is 30° C and no growth occurs at either below 10° C or above 40° C [57] and the weed is killed at temperatures below -30° C or above 43° C [58]. Plants may be killed by frost but unfrozen buds survive [11]. In Botswana the plant grows in the range of temperatures between 8° C and 30° C. Leaf surface hairs are usually damaged to produce white patches during high chilling winter nights of June and July months.

pH and Conductivity: Salvinia grows in the range of pH from 5.2 to 9.5 [59] and in Africa it has been seen to grow from 6.5 to 9.5 [18]. Field surveys indicate that salvinia can grow in water bodies with conductivities ranging from "100 to 1400 µS cm^{-1}" [59, 60] and can survive at about "2,000 µS cm^{-1}" [18]. Salvinia does "not colonize marine or brackish waters" [17]. In Botswana salvinia is found to occur in waters of pH ranging from 4.5 to 10.3 and grows in low conductivity waters of 20 µS cm^{-1} and at more than 580 µS cm^{-1} in the pools, lagoons, rain water pans and in wetlands.

Nutrients: The plant size and growth depends on available nutrients. Salvinia growth was "limited by N and P availability when tissue concentrations reached approximately 5% or more for N and 0.5% or more for P under laboratory conditions" [61 - 63]. Availability of nutrients in the water determines the growth and survival of salvinia colonies. In infertile and low nutrient water (N = less than 0.02 mg L^{-1}), salvinia had tough rhizome branches with thin large leaves and longer "roots" [45, 46]. In contrast, in fertile waters of lagoons, in wetlands and under overcrowded conditions, the weed has highly branched rhizomes with thick leaves and short "roots" [46]. The range of pH, conductivity and water soluble NPK nutrients in the various wetland habitats such as flowing waters, ponds and lagoons where the salvinia is commonly found in Botswana is presented in Table **3**.

Table 3. Range of pH, EC and soluble total nitrates, phosphates and potassium in various water habitats of *Salvinia molesta* infestations in Botswana. (Okavango Delta (Source: [51]); Kwando-Linyanti-Chobe (Source: [137]).

Nutrients	**Moremi Game Reserve - Okavango Delta (18 sites)**	**Kwando-Linyanti Rivers (15 sites)**	**Chobe River (6 sites)**
pH units	4.5 - 10.3	6.45 - 9.87	6.72 - 9.12
EC, µS cm^{-1}	20 - 580	106 - 215	59 - 880
NO_3-N mg L^{-1}	0.02 - 1.50	0.03 - 1.78	0.04 - 1.81
PO_4-P mg L^{-1}	0.02 - 0.90	0.01 -1.10	0.02 - 1.0
K mg L^{-1}	0.3 - 6.80	2.51 - 5.83	1.61 - 6.92

Tissue N concentrations ranged from 0.62 to 4.0% and tissue P from 0.03 to 1.07% dry weight under field grown plants [41]. The Australian average for concentrations of N in tissues of salvinia was 1.59%, while that for tissues from Papua New Guinea was 1.12% [63, 64]. In Botswana, the average percentage content of tissue N, P and K in healthy salvinia in the riverine systems is presented in Table **4**. When biocontrol mechanism is in place, there is always a loss or leaching of nutrients from salvinia tissue and hence comparisons are made between healthy, partially dying and, completly dying and sinking mat (Table **5**).

Table 4. Average NPK nutrient levels in percentage dry mass of healthy *Salvinia molesta* plants in Moremi Game Reserve in the Okavango Delta, Kwando-Linyanti and Chobe Rivers. Source: Okavango Delta (Source: [51]) and Kwando-Linyanti-Chobe Rivers (Source: [104]).

% % dry mass	**Moremi Game Reserve – Okavango Delta**	**Kwando-Linyanti Rivers**	**Chobe River**
N mg L^{-1}	1.949	1.282	1.841
P mg L^{-1}	0.198	0.062	0.174
K mg L^{-1}	2.018	1.804	1.393

Growth rates and density: Rates of growth and vegetative reproduction are significantly high in salvinia. Salvinia "grows more rapidly when provided with dissolved inorganic N as NH_4^+ rather than NO_3^- ions" [61]. "High levels of biomass production and doubling in less than 4 days occurred in salvinia in solutions with N and P combinations varying from 2 to 20 mg NH_4 - N L^{-1} and from 2 to 10 mg PO_4 - P L^{-1} [65]. It was reported that in Lake Kariba, Zimbabwe, the ramets doubled in 8 to 17 days [28]. In nutrient poor conditions densities form as high as 2500 ramets m^{-2}. Salvinia is 90% water by weight and dry biomass could be ranged from 250 to 600 g m^{-2} [21, 25]. In Botswana the fresh biomass of salvinia in m^2 was a minimum of 1.4 ±0.1 kg in wetlands among vegetation and a maximum of 6.0 ±0.5 kg in the open pools and lakes where the mat is tightly packed on the surface of water. The number of ramets in m^2 was in the range of 1945 to 2300 in dense mat growth. Fresh salvinia washed well in fresh water and processed under direct sunlight yielded 8% to 9% dry weight.

Dispersal and spread: Dispersal of salvinia is by vegetative fragments. Flooding can break up the plants while boats and vehicles act as carriers of the weed on intra- and inter-lake dispersal [66]. "Hippopotami in Africa and water buffalo in Australia" have been found to carry salvinia on their backs from one water body to the other [18, 50]. In Botswana common modes of dispersal are fishing activities, boat movement, water velocity, and also communities are believed to carry and spread the weed to some areas for local employment generation. Hippopotami carry the weed on their backs whereas elephants carry the plants by adhering to the legs and trunks.

Table 5. NPK nutrients in healthy, partially dying and in complete dying of *Salvinia molesta* plants in response to biocontrol process (source: [51]).

Condition	N mg L^{-1}	P mg L^{-1}	K mg L^{-1}
Healthy	1.949	0.198	2.018
Partially dying	1.55	0.102	1.512
Complete dying/sinking	1.3	0.082	0.933

4.6. Management

4.6.1. Physical Control Methods

The physical control options for controlling free-floating aquatic plants have generally involved the following management practices: (a) physical removal of the weeds directly by hand, or by using water-based or land-based mechanical harvesters; (b) destroying the weed infestations by cutting, shredding, or chopping targeted plants; (c) placing barriers to prevent colonization of other areas; and (d) modifying the environment or reducing input of soluble nutrients from point and non-point sources to minimize growth of the problem plant [11, 41, 66]. These methods are generally species specific, site specific and habitat specific. The merits and demerits of each method are discussed in greater detail [66, 67].

4.6.2. Physical Control - Botswana

Manual Removal: Manual removal became successful in controlling salvinia in the initial, minimal and uncrowded populations in Moboroga River and few areas of Boro River in the Okavango Delta. Similar successful manual removals elsewhere were reported [33, 68].

Booms and vegetation blockages: Several physical control methods like booms and earth dykes were erected prior to 1980s to control and/or to eradicate salvinia in Botswana. A floating boom was erected across the Kwando River near Shummamori (SM) for trapping and clearing salvinia manually [69]. Papyrus blockages at Shummamori in Kwando River, Lupala Island (LP) of Linyanti River (Fig. **2**) and on Gomoti River in the Okavango Delta were used as natural preventive measures not allowing the weed to infest other wetlands. Filters using chicken mesh were used in Khwai River of the Delta and maintained between 1998 and 2000 to prevent the spread of the weed in the downstream. Similar control measures, which require periodical inspection and maintenance, are reported around the world [68, 70].

Habitat alteration: Water-level drawdown is a relatively inexpensive technique for controlling aquatic weeds in seasonal rivers and lakes with sufficient water-level control structures [66, 41]. The dense biomass of salvinia in wetlands of Dombo and its nearby Oyi was dried by stopping the flow with an earth dyke maintained at inflow point between 1997 and 1998 [71] and a similar procedure was applied on Santantadibe River in 2003 near Ditshipi. Under the dry spell of summer characterized by low and restricted flooding and low rainfall, salvinia often forms thick mats in the seasonal wet areas. In such locations individual plants may survive through dry season under a mulch of dead salvinia plants [18]. Salvinia firmly adheres to the drying channel or stream bed and the tiny buds of the deeper layers of the weed do not dry easily as the moisture is maintained by the upper layers. Raking, drying and burning the weed has proved to be a reliable option in such stratified growth conditions to expose the deepest layer of plants for quick desiccation whereby the ramets of the plant would be killed prior to the arrival of new flood as employed in Mogogelo in April 1999 [71]. Thick mats that developed in "Xaxanaka Lagoon" were removed by hand with the assistance of Department of Wildlife in 1992" [72]. Reducing biomass in the areas of packed mat infestations by hand collection to hasten the biocontrol in perennial waters proved to be an effective exercise prior to the release of weevils as implemented in 1999 in Khwai River [71] and in 2004 in Ditshipi pools (Fig. **3**) [51]. However, the use of manual method is constrained by the cost of control, limited capacity to address large scale infestations and more importantly to control rapid growth of the weeds.

Bunding, fencing and drying of swamps - 1986 to 1992: Control of salvinia began immediately after its detection on 14 July 1986 in Lake Xini and on 4 July 1988 in Bodumatau wetlands [50]. The area infested in Xini was 800 m x 300 m and contained in a 25 km^2 pocket and covering 2 km^2 in Bodumatau. Fences were erected to restrict the animal movement (especially Hippopotami and elephants) and bunds were "constructed in the inflow channels to dry out" and control the weed in the infested swamps of Lake Xini (Fig. **4a**) [50]. Diesel-powered water pumps used in drying the above areas yielded substantial control of *S. molesta* augmented by the release of *C. salviniae* transported from Simaa Lagoon (Fig. **2**) of Linyanti River and released in Xini [50]. Similar operations were applied immediately after the detection of salvinia in Bodumatau. "Drying out Xini and Bodumatau areas in the Okavango Delta was an attempt to eradicate" salvina but the attempt "failed as the primary form of the mat was difficult to pick up among the vegetation". However, the confidence in integrating physical and biological methods increased through these operations without the use of chemicals. Unfortunately, the victory was short-lived as thick spread of salvinia appeared later in other wetlands of the Okavango Delta including Xini and Bodumatau. The Xini Lake and the major part of the wetlands in Bodumatau had been dry from 1990 to 2008 and slowly became flooded from 2009 onwards.

4.6.3. Ecosystem Approach

Prevention: Prevention is the best method by detecting weed infestations early for rapid response as applied in several wetland areas such as on Maunachira, Santantadibe and Thamalakane Rivers of the Okavango Delta (Fig. **3**). The port of entries has been regularly monitored to prevent importing invasive weeds from neighbouring countries. This is done through public awareness program enforcing "Aquatic (Weeds) Control Act" for restricting the sale, transport, and growing of weeds in home yards as achieved in Kasane and in Maun with respect to water hyacinth in 2002 and 2016 respecvely (Table **1**).

Integrated pest management (IPM): Integrated IPM approach employing "chemical, biological, physical, and public outreach" would be the best option for managing the weeds [41]. Botswana has stopped the use of chemicals in northern wetlands since 1976. However, integration of "physical and biological control" with public outreach methods has been proved effective measures for managing salvinia and other weeds right from 1986.

Filling the niche**:** The most effective way to achieve sustainable control is by "filling the niche" with native species that would help to prevent the spread of the invasive species [41]. Selection of suitable aquatic plants as a defense mechanism against an overgrowth of invasive species is one of the options. Salvinia has been found reduced to minimum levels by the extensive growth of indigenous aquatic plants including grasses in 2008 in Dombo and its associated Oyi wetlands

Nutrient management: Normally, some "water bodies receive inputs of nutrients and sediment" from the surrounding drainage basin as a result of "natural runoff, soil erosion, agriculture run-off, failing septic systems, deforestation, building and road construction" [41, 73]. Even though the above activities are minimal in the northern wetlands of Botswana, management strategies are in place to prevent the nutrient discharges through waste water contamination from the tourist lodges in the Okavango and Kwando-Linyanti-Chobe systems.

4.6.4. Chemical/Herbicidal Control

Herbicide control is a temporary measure and usually applied once or twice on aquatic weeds in any water systems due to adverse impacts on non-target organisms and water environment as well. The first attempts to chemically manage salvinia were made in Sri Lanka in the 1940's where "emulsifiable oils containing pentachlorophenol (wood preservative)" was used in rice paddies and waterways [33]. The effectiveness of the herbicides paraquat (1,1'-Dimethyl-4,4'-bipyridinium dichloride), diquat (1,1'-Ethylene-2,2'- bipyridinium dibromide), nitrophen (2,4-dinitrophenol), and dalapon (2,2-dichloropropionic acid) for control of salvinia was assessed in Malaysia [74]. Of these products, only paraquat and diquat showed potential herbicidal properties for salvinia. Paraquat applied as a foliar spray at a rate of 1.1 kg ha^{-1} controlled 100 percent salvinia in one week. Diquat at 4.5 kg ha^{-1} controlled 99% of the plants, but such a high rate was considered cost prohibitive. As a result of these studies, paraquat was used from the late 1960's through the 1970's to control salvinia in Zimbabwe, Kenya, Sri Lanka, Botswana, Australia, and Papua New Guinea [17, 33, 75]. AF 101 (diuron (3- (3,4-Dichlorophenyl)-1,1-dimethylurea) mixed with kerosene and calcium dodecyl benzene sulfonate was used successfully for large-scale treatment of salvinia in Australia [76]. Fluridone concentrations of 45 to 90 μg L^{-1} (ppb) and glyphosate (N-(phosphonomethyl) glycine) concentrations of 2.24 kg ha^{-1} were successful to control salvinia in Florida, USA [77, 78].

4.6.5. Chemical/Herbicidal Control in Botswana - 1972-1976

The first effort for the development planning on the weed control in Botswana began in 1972. The Department of Agricultural Research in the country applied the herbicide paraquat as an interim measure by knapsack and motorized sprayers using boats between 1972 and 1976 [72]. In a series of joint trials, Botswana and Namibia sprayed the herbicides paraquat and glyphosate using fixed-wing aircraft at Ponpon (PP) and Shaile (SL) on Linyanti River, Quega

(QG) on Lake Liambezi and Nungwe (NW) on Chobe River between 1975 and 1976 (Fig. **2**) [27, 79]. All these costly operations demonstrated that the principal difficulty encountered was in applying herbicides to the weed growing under canopy of thick vegetation such as papyrus, *Cyperus papyrus* L., tall grass *Miscanthus junceus* (Stapf) Pilg. and reed *Phragmites australis* (Cav.) Steud. Such inaccessible locations serve as reservoirs for re-infestation by the weed [72]. Although paraquat and glyphosate are registered for their use in Botswana, their application in the aquatic systems were stopped by the Government of Botswana after 1977 as a result of serious impacts on non-target aquatic species.

4.6.6. Biological Control Agents

The "first surveys for potential biological control agents for *S. molesta* were conducted" during 1961 to 1963 in the native range of *S. auriculata* in Trinidad, Guyana, northeastern Brazil and Argentina [80, 81]. About 25 phytophagous insect species were found associated with *S. auriculata* complex [81]. Out of these, three species were selected for further study and they are weevil *Cyrtobagous singularis* Hustache, a moth *Samea multiplicalis* Guenee, and a grasshopper *Paulinia acuminata* De Geer. The host-specificity studies were conducted at Belem, Brazil, and Trinidad between 1964 and 1965 [80].

After the discovery of the native range of *S. molesta* [16] research was conducted on other members of *S. auriculata* complex to explore possible biocontrol agents. All insect and mite species found on salvinia were listed in Forno and Bourne [82] who also indicated that the three main phytophages on *S. molesta* were those selected by Bennet [81]. The genus *Cyrtobagous* Hustache was originally thought to be monotypic, containing only *C. singularis species*, which was known to feed on various South American *Salvinia* species. *Cyrtobagous singularis* collected from Trinidad had been used unsuccessfully as a biological control agent for *S. molesta* during the 1970s in Botswana, Zambia [81, 83], and Fiji [84].

In 1980, a weevil thought to be *C. singularis* was introduced in Australia by the Council of Scientific and Research Organization (CSIRO) by importing from the native range of *S. molesta* in southeastern Brazil [85]. This weevil established and rapidly controlled the weed on Lake Moondara in northern Queensland, Australia [86]. Subsequently it was reported that the weevil from *S. molesta* collected from southeastern Brazil represents a species different from *C. singularis* [87]. Comparative studies determined that this was a new species, subsequently named *Cyrtobagous salviniae* by Calder and Sands [88]. Host range studies to assess feeding by *C. salviniae* were carried out in Australia on six plant species [89]. Several other insect species, various fungi, and a snail have been reported attacking salvinia in its exotic range and none has been reported to be effective on the weed [90].

Salvinia weevil *Cyrtobagous salviniae* Calder and Sands (Coleoptera: Curculionidae): The life history stages and descriptions of the weevil are well described [87 - 89, 91]. Commonly called "salvinia weevil", (Fig. **4b**) the adult male of *C. salviniae* (1.8 x 0.9 mm) is slightly smaller than the female (2.2 x 1.2 mm). Females do not oviposit below 21° C and eggs usually fail to hatch below 19° C. [41]. Newly emerged adults are brown, darkening to black in about 5 days [82]. Adults feed on the tender apical buds, young leaves and on roots. Larvae browse the young buds, the "roots" and tunnel the rhizome. Increased nitrogen stimulates an increase in oviposition [92] and feeding increases with increased temperature [89]. The combined effect of feeding by adults and larvae prevents growth by destroying meristematic tissues and destroying rhizomes, severing the root-shoot link. As a result the plant rots and becomes waterlogged and sinks [93].

Cyrtobagous singularis Hustache (Coleoptera: Curculionidae): The biology of *C. singularis* is almost similar to *C. salviniae*. Morphological differences between these two species, life history and feeding habits were described in detail [88, 91, 92, 94]. Adults of *C. singularis* feed on apical leaves, buds, rhizomes, and petioles [94] and do not tunnel rhizomes, hence not effective biocontrol agent.

Water lettuce moth *Samea multiplicalis* Guenee (Lepidoptera: Pyralidae): *Samea multiplicalis* occurs from southeastern USA to Argentina and has been collected in Trinidad, Guyana, Brazil, Uruguay and Panama from species of *Salvinia auriculata* complex [80, 85]. It is also commonly found on *Salvinia minima*. The life cycle, adult growth and ecological factors are described [95 - 97]. Adults are 6.5 to 10.5 mm long "tan, with brown and cream markings on both fore and hind wings" (Fig. **5a**) [98]. Larvae (Fig. **5b**) prefer young plant material and feed the leaves of tertiary growth form. The moth is heavily parasitized in Trinidad and is heavily predated on by semi-aquatic syrphids, dyticids and hydrophilids [80].

Salvinia grasshopper *Paulinia acuminata* DeGeer (Orthoptera: Pauliniidae): *Paulinia acuminata* (Fig. **5c**) is a humid-loving insect adapted to living on floating mats of host plants and can complete its development on *Salvinia* spp., *P. stratiotes*, *Azolla* sp., and *Hydromystria* sp. and feeds on other species as well [80, 99] but failed to complete the full development on water hyacinth [99]. Adults and nymphs eat leaves of secondary and tertiary growth forms. A significant reduction of salvinia on Lake Kariba occurred in 1973/74, following the release of *P. acuminata* in 1970 [11]. Chisholm [100] demonstrated that densities of more than 85 *P. acuminata* m^{-2} feeding for 24 days was required to reduce production of new leaves. Field populations in Africa observed from 45 to 54 *P. acuminata* per m^{-2} grazed up to 87% of leaves without affecting apical or lateral buds or killing the plants [99].

Fig. (5a). *Samea multiplicalis* adult.

Fig. (5b). *Samea multiplicalis* larva.

Fig. (5c). *Paulinia acuminata* adult (Photos by P. Room, CSIRO, Bugweed.org).

4.6.7. Biological Control: Botswana - 1972-76

The entomologists of Agricultural Research in the country imported two insects, a weevil *C. singularis* and the grasshopper, *P. acuminata* recommended by the Commonwealth Institute of Biological Control (CIBC) in Trinidad**.** About 3370 *P. acuminata* and 1550 *C. singularis* were air released from Ponpon (PP) to Shaile (SL) in Linyanti River and at Nungwe (NW) near Kazungula on Chobe River between 1971 and 1975 (Fig. **2**). It was found that the breeding rates of grasshopper was very low in 1982 assessments due to acclimatizing to Botswana winter nights, as the temperatures were lower than 27°C than those reported from its native range in Central America. The evidence of predation by little bee-eaters and jacanas were perhaps also a significant factor for their low numbers. Hence, *P. acuminata* was regarded as no more than entomological curiosity in terms of biological control program for salvinia in Botswana. A moth, *S. multiplicalis* recommended by CIBC was released in 1972 and did not control the weed [84]. Beyond reporting the release of *C. singularis* at Ponpon (PP) and Shaile (SL) (Fig. **2**), the entomologists did not make any further reference to its activity except to emphasize that its small size and cryptic behavior made it difficult to trace

[72]. However, Schlettwein [82] found the widespread distribution of *C. singularis* in the salvinia areas albeit at low densities ranging from 0.13 to 8.9 adults per kg fresh weight of salvinia in Caprivi of Namibia and also in the released areas of Linyanti and Chobe [49, 101]. *Paulinia acuminata* was also tried on salvinia in Zimbabwe in 1969 and 1971, Kenya and Zambia in 1970, Sri Lanka in 1973 and 1978, India in 1994 and in Fiji in 1975, but failed to establish [11].

Cyrtobagous salviniae– Australian success: Adults of *C. salviniae* were collected in its native range in southeastern Brazil by the CSIR Australia and subsequently released in Lake Moondara infestation in northeastern Queensland, Australia in 1980. The success story of *S. molesta* control by *C. salviniae* was published in the 'Nature Journal' in November 1981 [86]. The news of the event reached Botswana in March 1982.

Arrival of *C. salviniae* to the Okavango Delta – July 1986: The Department of Water Affairs (DWA), Namibia acted fast and imported two consignments of adult *C. salviniae* weevils from Entomology Division of the CSIRO, Australia. The first 144 insects imported in 1982 failed to breed. A second batch of 500 (of them 20 weevils died during transportation) arrived in September 1983 and reared successfully in three portable pools where salvinia was grown with nutrients in the DWA Campus, Katima Mulilo in Namibia (Fig. **2**). The first 450 adult weevils were released at Sitwa in side channel of Kwando River in December 1983 (Fig. **2**). By March 1985, over 10,000 insects had been released at various sites of Lake Liambezi, Chobe River and in Caprivi [29]. The weevils thus established in due course of time in Kwando-Linyanti system with the aid of water currents. The DWA in Botswana transported *C. sa*lviniae from Simaa Lagoon of the Linyanti River and introduced in the Xini Lake of the Okavango Delta on 20 July 1986, one week after the discovery of *S. molesta* infestation (Fig. **2** and Fig. **4a**) [50].

In 1984, a special working group to co-ordinate biological control research in aquatic weeds was set up by SARCCUS (Southern African Commission for Conservation and Utilization of Soil) comprising representatives from Botswana, Namibia and South Africa. At its first meeting in October 1984, the Namibians reported that a viable breeding colony of the weevil, *C. salviniae* was developed at Katima Mulilo from the stock imported from CSIRO, Australia. Meanwhile the University of Botswana with the help of Australian scientists had drawn up a project to direct a research program for the control of salvinia [72]. The DWA, Botswana contracted Dr. Forno from CSIRO, Australia and she arrived in February 1986 to assist in the implementation of salvina Biological Control Program (SBCP) in the country. She made seven visits to the country as Aquatic Weed Consultant and her last visit to the country was on 21 July 1999. SARCCUS became defunct in 1998 and merged with the 'Water Sector' under Southern African Development Community (SADC).

In July 1984, the weed control activities were transferred from Agriculture Research to Hydrology and Water Resources Division in the DWA, Botswana as a new unit called "Aquatic Vegetation Control Unit (AVC Unit)" at Maun as an authorizing center to protect the wetlands from the AIS in the country. In January 2000, another AVC Unit office was started in DWA, Kasane for effective management of weeds in the Kwando-Linyanti-Chobe system [102]. In spite of some significant progress made prior to 1996, lack of profound scientific approach in the aquatic weed control program was discernible. With the appointment of a Plant Scientist in August 1997, the matters improved in the aquatic vegetation control management. New strategies aiming at effective monitoring research procedures were drafted and implemented [102]. The efficacy of biological control weevil on salvinia infestations was undertaken in 1998 and showed that biocontrol was achieved within a year in stagnant water bodies compared to the dynamic flowing rivers where control could be achieved in two to three years [103].

4.6.8. Systematic Monitoring Sites

Unlike prior to 1997, systematic monitoring sites were demarcated in the infested areas of Kwando-Linyanti-Chobe River system (Fig. **6**) and in the Okavango Delta (Fig. **7**) between January and March 1999. The monitoring sites were fixed based on the accessibility in every riverine system. The distance between the sites in most cases was between 3 and 5 km and for few sites, it was more than 7 to 10 km due to accessibility problems. Breeding pools for *C. salviniae* were erected in 1998 at Xakanaxa DWA camp to obtain necessary stock for their releases. The weevil with its larvae and pupae were collected in the areas of high density weevil populations in the field as well as from the weevil breeding pools and seeded in sites of infestations with less biocontrol between April 1999 and December 2000. This was one of the biggest releases ever undertaken in Botswana [101]. The weevil populations were steadily built up from zero to 87.3 ±6.8 weevil number per kg fresh weight of salvinia in some sites, while in other sites the weevils increased from 21 ±0.9 to 106.7 ±8.8 number per kg fresh weight of salvinia. By 2003 the dense infestations of salvinia were relatively brought under control in upper Kwando, Shummamori, Lebala pools and its wetlands, Selinda Canal, Sajaawa, Kawedum, Kings Pool, and Hyena Camp in Kwando-Linyanti Rivers; and Kazungula, Serondella, Ihaha, Ngoma bridge, several pools and side canals of Chobe River (Fig. **6**). In the Okavango Delta such releases made between 1999 and 2000 yielded similar significant impact on the control of salvinia in Paradise Pools, Xini, Bodumatau, Oyi, Dombo, Dasakao, Xakanaxa Lagoon, Khwai River, Abaqao and Mogogelo (Fig. **7**). Currently salvinia has been found under balanced levels between salvinia and the weevil in 6 major rivers, 9 minor rivers, 23 lagoons/lakes, 34 wetland pools and ponds spanning over the "Okavango Delta and Kwando- Linyanti- Chobe River system". Based on 8% dry weight estimates obtained for 6.0 ±0.5 kg tertiary salvinia mat per m^2, the calculated dry biomass in various controlled areas is presented in Table **6**.

Table 6. Biomass of *Salvinia molesta* calculated in various rivers, pools and lakes in the Okavango Delta, Kwando, Linyanti and Chobe Rivers and year of control achieved. Example: 0.154 km^2 equals to154000 m^2; 154000*0.48/1000 = 73.92 or 73.9.

River/Wetland	Pool/Lagoon	Total area (km^2)	Area infested (km^2)	Dry biomass (tons)	Control achieved
OkOkavango Delta					
Khwai River	Dombo Lake	0.325	0.154	73.9	Oct. 2001
Khwai River	Oyi Pool	0.726	0.288	138.2	Dec. 2003
Khwai River	Paradise pool	0.083	0.040	19.2	Oct. 2000
Khwai River	HATABl & 4th Bridge Pools	0.071	0.039	18.7	Oct. 2015
Xini River	Pools	0.194	0.117	56.2	DeDec. 2003
Xini River	Xini Lake	0.238	0.232	111.4	Jan. 2010
Mogogelo River	Black pool	0.026	0.026	12.5	Nov. 2012
Mogogelo River	Wetland pools	0.055	0.027	13.0	Mar. 2006
Mogogelo River	Abaqao pools	0.096	0.050	24.0	Oct. 2002
Santantaidibe River	Ditshipi Pool 1 & 2	0.391	0.364	174.2	Nov. 2005
Wetland Channel	Bodumatau pool 1 & 2	0.257	0.115	55.2	May 2012
Kwando-Linyanti-Chobe River system					
Kwando River	Lebala pools	0.360	0.150	72.0	Feb. 2002
Kwando River	Selinda canal	0.068	0.038	18.2	JaJan. 2003
Chobe River-Ngoma	Wetland poolsspan>	0.016	0.012	5.8	MaMar. 2012

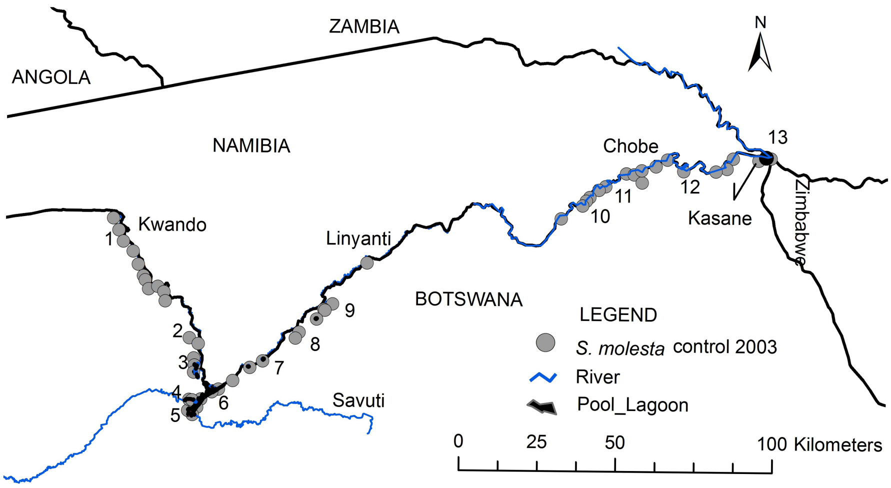

Fig. (6). Distribution and successful control of *Salvinia molesta* with its weevil *Cyrtobagous salviniae* in Kwando-Linyanti-Chobe Rivers. 1, 2 and 3 Kwando River = 16 sites; 4 Selinda Canal = 2 sites; 5 Zibadianja Lagoon = 5 sites; 6, 7, 8 and 9 Linyanti River = 11 sites; 10, 11, 12 and 13 Chobe River = 17 sites. Total monitoring sites = 51.

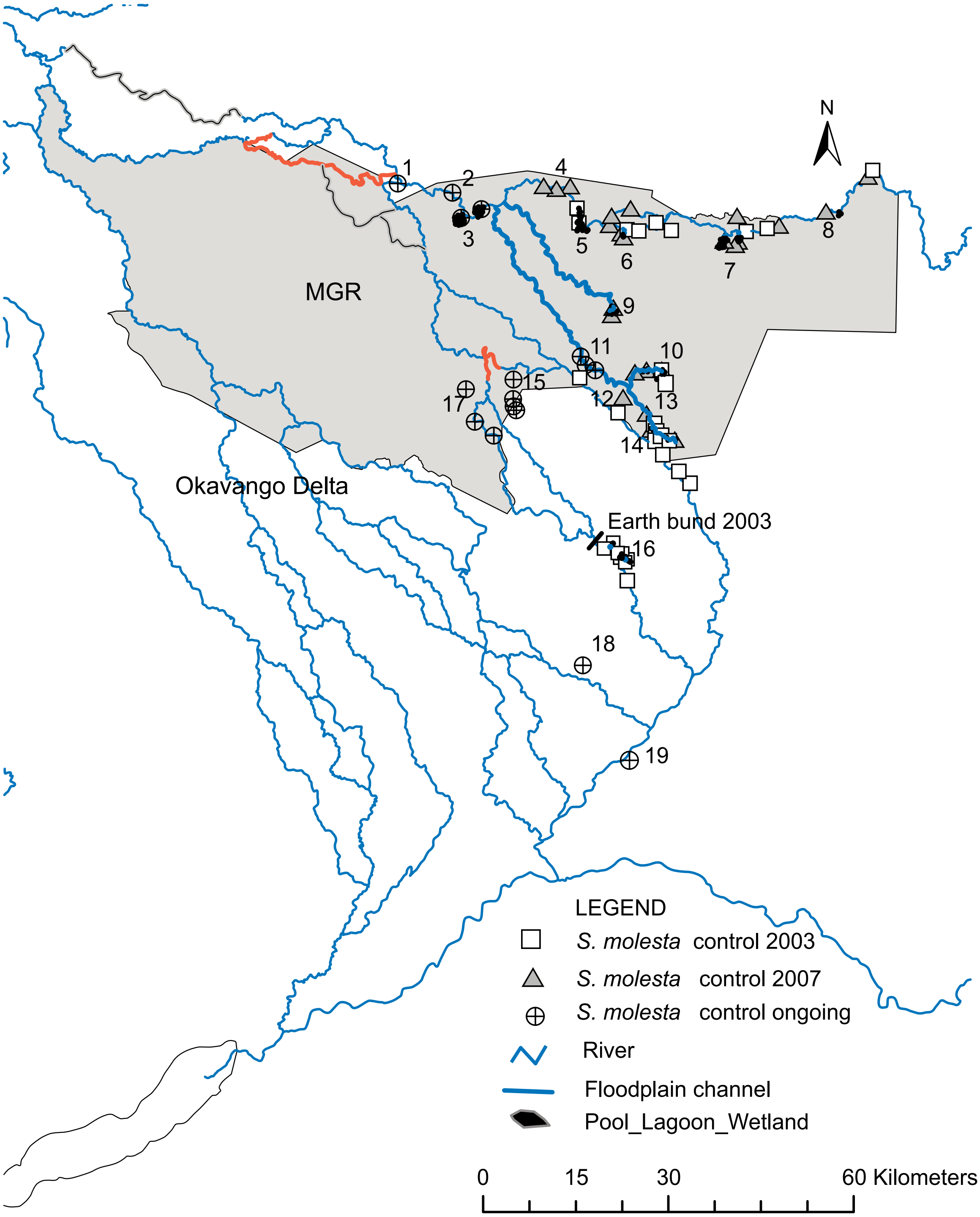

Fig. (7). Distribution and successful control of *Salvinia molesta* with its weevil *Cyrtobagous salviniae* in the Okavango Delta. Established Biocontrol sites: 1, 2, 3, 4 and 5 Maunachira River = 11 sites; 6, 7 and 8 Khwai River = 19 sites; 9 Bodumatau = 2 sites; 10 Xini = 4 sites; 11, 12 and 13 Abaqao and Mogogelo Rivers = 9 sites; 14 Gomoti River = 6 sites; 15 and 16 Santantadibe River = 10 sites; 17 Matsibe River = 3 sites; Biological control ongoing: 18 = Boro River = 1 site; and 19 Thamalakane River = 1 site. Total monitoring sites = 66 sites.

4.6.9. Establishment of Salvinia Weevil: After 2003

Having successfully controlled *S. molesta* in some of the above areas listed (Table **6**), there were no significant dense infestations noticed in the Okavango Delta and Kwando-Linyanti-Chobe River system after 2003. However, new infestations were observed in Xini Lake in 2010 and Bodumatau pools in 2012 after a period of 30 years as the lake and pools became wet as a result of higher inflows into the Delta. Salvinia mats that floated downstream slowly increased in multiple proportions to cover the Xini Lake and Bodumatau pools in less than five months period. Weevils that were maintained on the residual mats in the upstream, floated downstream to reach Xini and Bodumatau, steadily built up and control was achieved in 11 months without further release of the weevil. This clearly implies that the weevil had been well established in the upstream due to the releases made in 1999 and 2000 and continued to live at equilibrium with salvinia. Instances of similar kind were observed in Mogogelo, Khwai River pools and at Ngoma on Chobe River in 2012 and in four hippo pools in 2015 in the Okavango Delta.

Fig. (8ab). *Salvinia molesta* biocontrol in the presence of *Cyrtobagous salviniae* at 4th Bridge Hippo Pool, Okavango Delta (Photo: By Kurugundla).

5. *PISTIA STRATIOTES* L. - ARACEAE

The first descriptions of water lettuce, *P. stratiotes* are by ancient Egyptians and by Greek philosophers Dioscorides and Theophrastus [105, 106]. It was first reported from Florida in 1765, and hence led to the belief that this plant could be a native to North America [107]. The presence of co-evolved herbivorous insects in South America on the plant [108, 109] suggested, however, that water lettuce originated from South America. "Water lettuce use as a medicine and as fodder for cattle and pigs might have resulted in relatively rapid widespread distribution" in tropical and subtropical regions of the world" [34].

5.1. Distribution in the World

It is a serious pest in some parts of the tropics, but generally of less importance than other exotic floating water weeds like *E. crassipes and S. molesta* [12]. In most cases, the plant is abundant in tanks, ditches, and waste water discharge streams in villages and towns. Water lettuce has been found in Australia for the last 50 years [110] and has been newly recorded from several European countries (Austria, the Netherlands, Portugal, Russia, Slovenia, and Spain) which could be attributable to the aquarium trade [111] and is absent in Antarctica [36]. In Asia and China it has been a serious concern [112, 113] and it forms dense mats in Pantanal and becomes conspicuous in several impoundments in South America causing eutrophication [114]. In Africa, it has received most attention since the early 1960s and is of minor importance in South Africa [115] and in Botswana [116]. It is also found in Zimbabwe [117], Nigeria and other African countries [118].

5.2. Biology and Ecology

Taxonomic position: *Pistia stratiotes* is a monotypic species and its systematic position is: Division: Angiospermae, Class: Pteridophyta, Order: Alismatales, Family: Araceae, Sub-Family: Aroideae. USDA [119] places the species in the subfamily Aroideae with the other genera. The plant is most commonly called "water lettuce, water cabbage and Nile cabbage". *Pistia* is from the Greek '*Pistos*' meaning 'liquid', referring to the aquatic habitat of the plant; '*stratiotes*' also from the Greek means 'soldier like' [36].

Description: Water lettuce consists of a rosette of obovate to spatulate, velvety, light-green leaves up to 40 cm long in African and American clones (Fig. **9a**), covered by short hairs, which trap air bubbles and thus enable buoyancy. The lower surface of leaves is densely hairy, with longitudinal veins. Roots are small and leaves are short, narrowly cuneate up to 10 cm in plants that grow in waste water contaminated canals, ponds, ditches and in water-saturated soils. The plants that grow in poor nutrient waters have longer feathery roots that hang freely from a small rhizome in the water than in the nutrient-rich habitats [111].

Growth and reproduction: Water lettuce commonly colonizes new areas through vegetative reproduction by stolons. The stolons are produced from axillary buds through elongation of internodes, which produce daughter plants (ramets). The ramets break off after developing roots either by accidental means or by decaying of stolons. Inflorescence is a spathe, axillary, 2-4 cm long, greenish yellow, hairy with ciliolate margin, constricted between the female and male flowers. Spadix is shorter than and partly adnate to the spathe at the base with one female flower below and, male flowers are above represented by 2 to 8 stamens with 4 - celled anthers (Fig. **9b**). Ovary is 1-celled with many ovules and there is no perianth. The spathe below the constriction opens first in the morning hours to expose the wet stigma, whereas the male flowers remain enclosed. Some hours later, the spathe opens completely and exposes male flowers [111]. The female flower is represented by the ovary and short stout style with stigma entire. After fertilization, the small peduncle bends and pulls the developing fruit (2 mm long) underwater where the seeds are released [120, 121].

Dispersal and seed dynamics: Dispersal is by vegetative means and also potentially by seed (Fig. **9c**). Daughter plants detach from parent plants and get dispersed either by water currents or by animals. "It was originally thought that water lettuce did not produce viable seeds", but seed production has now been confirmed in Africa [111], India [122], South America [123], USA [124], South-East Asia [125], and central Europe [126]. In South Africa, one fruit per plant with 4-6 seeds per fruit, 4-11 seeds per fruit in Australia [127], 4-9 seeds per fruit in Brazil [123], 6-10 seeds per fruit in India [122], and 2 fruits in a rosette with a range of 1-17 seeds per fruit averaging 4 seeds per fruit in the USA [124] have been recorded.

Seeds sink to the bottom of the water body [120, 121] where they form a persistent seed bank (densities up to 4000 seeds m^{-2}) [124]. Seeds germinate readily in warm (>20° C), shallow water under high-light intensities [128]. Seeds remain dormant for long periods in dry sediments [124] and readily germinate when rehydrated during rains. Seeds do not germinate at temperatures less than 20°C; but survive at least two months in cold water at 4°C and several weeks in ice at –5°C [111].

Uses: The plant is used for methane production and as animal feed [129] or green leaf manure [130]. As the plant bio-accumulates considerable quantities of heavy metals, use of water lettuce as cattle feed is limited [131]. The plants are grown to clear biological waste of water treatment plants [132] or polluted ponds [133]. Water lettuce is also used to reconstruct wetlands [134] or to monitor water quality in rivers [135]. The plant is used in medicine to cure asthma in India [136].

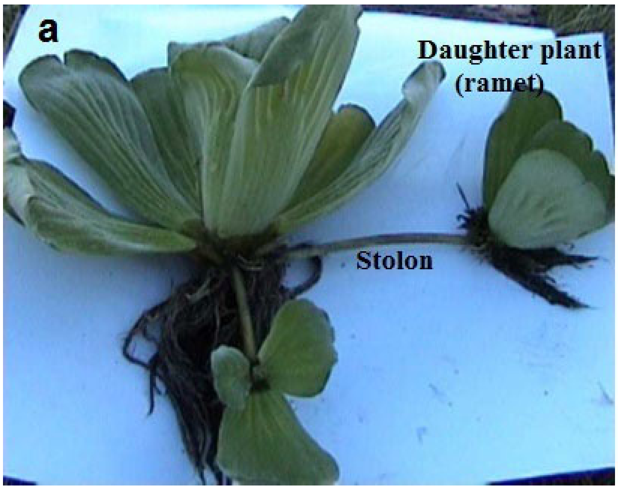

Fig. (9a). *Pistia stratiotes* habit.

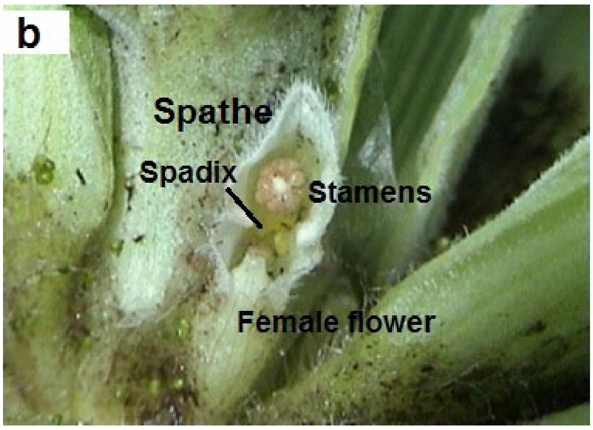

Fig. (9b). Inflorescence.

Fig. (9c). *P. stratiotes* capsules.

Fig. (9d). *Neohydronomus affinis* adult.

5.3. Historical Spread in Botswana

The first occurrence of water lettuce in Botswana was recorded in the Chobe River, and in Zibadianja Lake and Selinda Canal on the Kwando River, in 1986 [137]. Between 1990 and 1998 the weed infestation was sporadic in Selinda Canal and in the western part of the Zibadianja Lake because of low-flood events on the Kwando River. The weed increased to a thick infestation covering the Selinda Canal and western part of the Lake as a result of above-average rainfall at Selinda (554 mm in 1999, 656 mm) in 1999/2000 rain season supported by higher flows in the Kwando River reaching the weed-infested areas out of Dumatau Lake [138]. The weed covered Selinda canal for a distance of 2.7 km (0.230 km^2) in 1999 while the area of surface coverage was 0.065 km^2 in the Lake (Fig. **10b**). Selinda Canal had become perennial from 1999 to 2005 while the Lake dried by June 2003, and refilled in December 2003 after the clearance of vegetation blockages in the Lake's supplier streams [138]. This resulted in the activation of seed bank and by January 2004, water lettuce spread over an area of 0.003 km^2 in the Lake (Fig. **10b**). The weed was manually removed in the areas before fruit maturity [116].

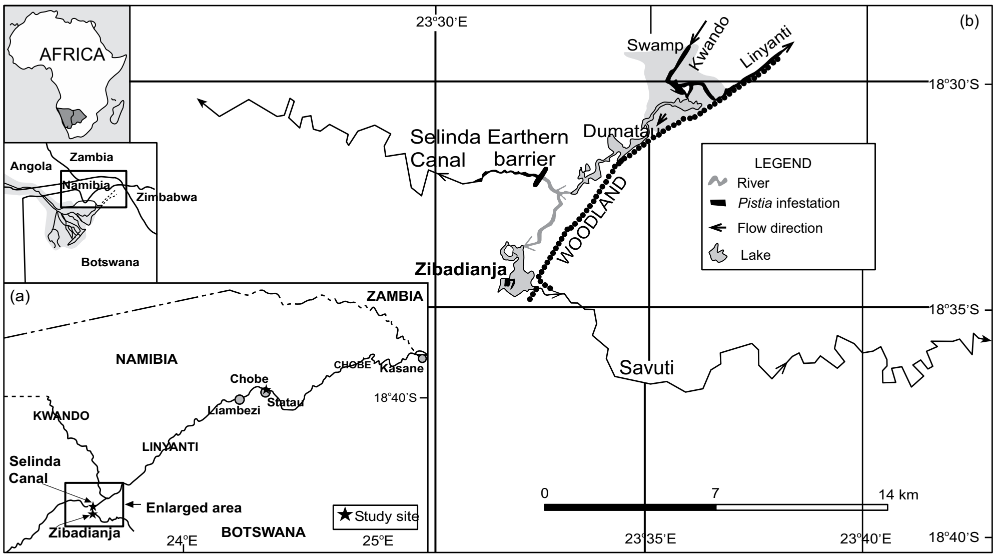

Fig. (10). (**a**) Sites of *Pistia stratiotes* infestation in Selinda Canal and Zibadianja Lake on the Kwando River and at the Chobe site on the Chobe River; (**b**) details of location of *P. stratiotes* infestation in Selinda Canal and Zibadianja Lake between 1999 and 2004. (Source: [116]).

The Chobe River forming the border between Botswana and Namibia connects to the Kwando - Linyanti River system *via* Lake Liambezi in Namibia. Water lettuce was "first recorded in the Chobe River in 1986" [137]. In 2000, isolated patches of water lettuce with its biological control weevil were observed in a 3.4 km-long infestation in Chobe River close to Satau village (Fig. **10a**). The release of the weevil *N. affinis* at this site in 1987 has kept the weed under control since that time [116].

5.4. Negative Impacts in Botswana

The impacts of water lettuce are directly related to tourism in Botswana with changes in water nutrients. Since its eradication in Selinda Canal and Zibadianja Lake in 2005, such impacts have become negligible. Even though, water lettuce is still localized in Chobe River it does not pose any environmental problems as the infestation has been found to be under control with its biocontrol weevil *N. affinis.*

5.5. Factors Affecting Growth

Water lettuce develops within the range of 15° C and 35° C, with optimum growth achieved between 22° C and 30° C and appears to thrive particularly well in ecologically disturbed habitats and in impoundments. Growth of water lettuce is inhibited at pH 4 and optimal at pH 7 [128] and increased growth is linked to increased concentrations of nitrogen, phosphorus, and microorganisms, lower pH, and found to reduce total species diversity of planktonic forms [139]. In Botswana water lettuce had been found to grow at temperatures ranging from 8.5° C to 30° C, having pH from 5.5 to 10.1. Changes in water nutrients before and after the plant eradication in Selinda Canal is presented in Table **7**.

Table 7. Some physical-chemical characters of water in Selinda canal before and after eradication of *pistia stratiotes*.

Nutrients	Before control	After control
pH units	6.95	7.65
EC, $\mu S\ cm^{-1}$	315	143
Dissolved O_2	2.1	4.9
NO_3-N mg L^{-1}	4.7	0.77
PO_4-P mg L^{-1}	2.8	0.16
K mg L^{-1}	7.9	3.7

5.6. Management

5.6.1. Physical and Herbicide Control

Physical hand picking, mechanical removal (using harvesters) and the installation of booms on slow flowing rivers are often practiced. Among the herbicides: diquat, glyphosate, 2, 4-D were evaluated for herbicide control of water lettuce in South Africa [140]. Botswana applied regular physical removal to eliminate the weed [116].

5.6.2. Biological Control Agents

To date, 46 species of phytophagous insects have been recorded on *P. stratiotes* (South America: 25 species, Asia: 13 species, Africa: 8 species) [109]. Most of these are oligophagous or polyphagous, but 11 monophagous insect species belong to *Neohydronomus, Pistiacola*, and *Argentinorhynchus.* The pupae of *Argentinorhynchus* require the water body to dry before adults emerge, hence not considered as biocontrol agent. Overall, only two species, a weevil, *Neohydronomus affinis* and a noctuid moth, *Spodoptera pectinicornis* have been used as biological control agents of water lettuce and however, only *N. affinis* has been widely used due to its effectiveness [111].

Neohydronomus affinis Hustache (Coleoptera: Curculionidae): The native range of *N. affinis* (Fig. **9d**) is Rio Grande do Sul of southeastern Brazil. The weevil was collected in Buenos Aires, Chaco, [141] and Formosa in Argentina and at Piracicaba in Brazil and described it as *N. pulchellus* Hustache, but was subsequently elevated and identified as *N. affinis* Hustache by O'Brien and Wibner [142]. *Neohydronomus affinis* (1.7 - 2.3 mm long) is brown to bluish grey with dense plumose scales on the elytra, with a nearly straight rostrum that is strongly constricted ventrally at the base. Adults feed on the leaf surface and later on internal spongy tissue or between the longitudinal ribs on the leaf under surface producing circular holes [142]. The larvae (2.5 - 3.0 mm in length) "feed on the basal leaves and mine the spongy leaf tissue" and transform to naked pupae (4-5 days) within leaf-tissue pockets. Weevil development takes place between 21°C and 27°C, however weevils survive up to 35° C [143]. Depending on weevil density, adult feeding and burrowing along with larval mining can kill plants (128 weevils per plant killed the plants in 3 days). At peak field densities of about 8 weevils per plant showed little damage for several days before collapsing totally [141]. .

Success of *N. affinis*: The first attempt of classical "biological control of water lettuce" was implemented by CSIRO Australia [110]. *Neohydronomus affinis was* collected at Pelotas, Brazil, and brought to Australia and released near Brisbane in 1982 after conducting host specificity tests on several water and wetland plants [110, 143, 144]. With the outstanding success in Australia, several countries used *N. affinis* to control *P. stratiotes*. The weevil has now been well established in Chobe River in Botswana [116]; Republic of South Africa (RSA) in the water pan in Pafuri area, Sunset Dam (Kruger National Park) [145]; Sabie River, a dam in Mmabatho [140, 146]; Sepik River and at Bulolo in the Morobe Province in Papua New Guinea [111]; Florida and Texas in USA [147, 148]; Manyame River and upstream of Lake McIllwaine in Zimbabwe [117, 149]; Central Cuvette, Brazzaville and in the southern Kouilou Province in Congo [150]; Kenya [115]; Djoudj National Bird Sanctuary of Mauritiana; Diawling National Park of Senegal [151]; southern Mono Province and northern Borgou Province in Benen [152]. In conclusion, in tropical regions, control could be achieved 100% in 1-2 years while in subtropical climates *N. affinis* populations decline to allow water lettuce to grow unchecked for a portion of the year and levels of biological control therefore fluctuate strongly [111].

Water lettuce moth *Samea multiplicalis* Guenee (Lepidoptera: Pyralidae): Water lettuce moth, commonly found on water lettuce and water hyacinth in Florida feeding on the inflated leaf petioles is "similar to the closely related water hyacinth moth *Niphograpta albiguttalis* (Warren)" [95]. Larvae feed on the young buds, eat mature fruits and consequently destroy enclosed seeds.

Spodoptera pectinicornis (Hampson) (Lepidoptera: Noctuidae): *Spodoptera pectinicornis* is native to India, Sri Lanka, Thailand, Indonesia, and Papua New Guinea [112]. This small grayish-speckled moth has bipectinate antennae and are conspicuous in the male. Although the species was, and still is, used for controlling water lettuce in Thailand [153], no detailed quantitative evaluation of the impact of *S. pectinicornis* in Asia is available. *S. pectinicornis* proved to be ineffective in Florida because of predation by birds, ants, and spiders [154].

5.6.3. Management - Botswana

The Department of Water Affairs, Botswana imported 437 *N. affinis* weevils in 1987 from the CSIRO Australia [137]. Upon their arrival, the weevil was mass-reared in artificial pools and released on water lettuce infestations in the Selinda Canal in November 1987, and three months later in Zibadianja Lake and the Chobe River. However, "no post-release evaluation has been carried out" [116].

There was a sparse infestation of the weed in the beginning of the growing season in 2000. The extent got magnified through vegetative propagation in 2002 at the rate of 5.2 (±0.3) stolons per plant in Selinda canal (Fig. **11a**). The "weevil became locally extinct in the seasonally flooded areas of the Selinda Canal and Zibadianja Lake between 1990 and 1998, as it lost its food source due to the cycle of wet and dry regimes". Water lettuce had been constantly under controlled levels in the presence of *N. affinis* in the perennial areas of Chobe River near Satau village [116].

In Botswana, field studies showed that each plant had a mean of 5.4 ± 0.2 fruits (Fig. **9c**) per plant with a range of 3-7 per plant and 30.3 ± 1.4 with a range of 18-42 (highest ever recorded) seeds per fruit. The matured seeds obtained in August 2002 from the plants gave 88.8% germination. Soil samples collected at random sites in the infested areas containing dormant seeds yielded 62.6% and 63.5% germination in Zibadianja and Selinda Canal in 2000 and 2002 respectively suggesting that the seasonal re-infestations were from the seed bank [116].

Eradication: Firstly, it was aimed to determine the presence of seed bank of water lettuce and its regeneration capacity in the seasonal areas of the Selinda Canal and Zibadianja Lake. Secondly, whether it was possible to eradicate the weed in the seasonal areas by continuous application of physical removal prior to the fruit maturity. To accomplish the task "an artificial earthen barrier or dyke was constructed in September 1999 across the Selinda Canal well upstream of the point of infestation using earth-filled plastic bags (Fig. **10b**). This provided an opportunity to dry out the canal and to regulate the water flowing downstream as and when required between 1999 and 2003 [116]. . By the method of regular physical removal prior to seed maturity, water lettuce thus eradicated in Selinda Canal (11a, and 11b) as well as in Zibadianja Lake by 2005.

By regulating the water flow at bund to the downstream, the seeds were allowed to germinate in the canal. Consequently the grown seedlings were physically removed between 1999 and 2003 prior to the seed maturity on the plants. By this method of continuous physical removal, seed germination was declined from 63.5% in December 2002 to 31.7% in September 2003. About 80 plants were collected by hand in "2004 growing season and only four plants in 2005 and none afterwards in Selinda" (Fig. **11b**). Low plant density (34.6 ±1.0 in m^2), lesser number of fruits per plant

(4.3 ±0.3), seeds per fruit (19.9 ±2.2) and stolons per plant (2.4 ±0.2) recorded in Chobe River might be attributed to the occurrence of weevils at the rate of 8.2 ±2.2 per kg number on water lettuce. When water was drawn down seasonally, "baboons uprooted the plants and fed selectively on the rhizomes of water lettuce, resulting in the death of the seedlings". Thus, the possible role of baboons in assisting in the control of water lettuce requires further investigation [116].

Fig. (11a). *Pistia stratiotes* covering Selinda canal in August 2002.

Fig. (11b). Selinda Canal after eradication of *Pistia stratiotes*.

6. *EICHHORIA CRASSIPES* (MART.) SOLMS-LAUB. - PONTEDERIACE

Water hyacinth is a free- floating plant indigenous to tropical Amazon basin in South America [155], but has been spread throughout the world. Infestations continue to plague fresh water bodies in Tropical Africa [156], India [157] and China [158]. It has taken advantage of most of the nutrient rich systems, becoming highly invasive and damaging [159].

6.1. Distribution in The World

Water hyacinth was first reported outside South America in "New Orleans in 1884" [160] and "by the end of nineteenth century, it was spread to Egypt, India, Australia and Java" [155]. Water hyacinth was spread to Venezuela and the larger Caribbean islands by anthropogenic activities and in Africa, it was first reported in Egypt in 1879 [161]. Subsequent infestations were recorded in Africa including Zimbabwe in 1937, Mozambique in 1946, Ethiopia in 1956, Rwanda and Burundi in the late 1950s, Tanzania between 1955 and 1959, Kafue River in Zambia in the 1960s, the Shire River in Malawi in 1968, Lake Naivasha in Kenya in 1986 and in South Africa in 1970s [7, 162]. The plant was recorded from Lakes Kyogain, Uganda in 1988-1989, Victoria in 1989-1990, Malawi/Nyasa in 1996 and Tanganyika in 1997 [15]. It was first reported in Cameroon between 1997 and 2000 [163] and dominates in the river water bodies in Nigeria [10].

6.2. Biology and Ecology

Taxonomic position: *Eichhornia crassipes* belongs to Division: Angiosperms, Class: Monocotyledonae, Order: Commilinales, Family: Pontederiaceae. All eight species of the genus *Eichhornia* originated in South America, except *E. natans* (P. Beauv.), which is native to tropical Africa [155]. Only *E. crassipes* is regarded as an invasive weed. Its common name is 'water hyacinth'.The genus *'Eichhornia'* named after J. A. Eichhorn (1779 - 1856), a Prussian Minister of Education in the 19th century; '*crassipes*' in Latin '*crassus*' means thick; *'pess'* means a foot; and alludes to the swollen leaf stalk.

Description: Water hyacinth displays two different morphologies on the basis of conditions in which it grows. In the first form, the petioles are elongated and bulbous (Fig. **12**) and can reach up to 1 m in length in open water areas. In the second form, the plants are short (less than 30 cm) and bulbous, with kidney-shaped and circular leaves that grow along the edges of water bodies and contaminated areas of high nutrient waters [164]. The bulb is spongy containing air chambers that help to keep the plant buoyant. The 6-10 glabrous leaves are arranged in basal rosettes, each leaf lasting up to 6-8 weeks before senescence. Rhizome and the fibrous feathery roots remain submerged. Roots are longer in low nutrient conditions than in high nutrient waters [15].

Growth and reproduction: Water hyacinth commonly colonizes new areas through vegetative reproduction and development of horizontally growing stolons**.** Stolons are produced from axillary buds through elongation of internodes, which produce the daughter plants (ramets) (Fig. **12**). Each ramet produces roots and subsequently breaks into an individual plant. The populations increase rapidly doubling under suitable conditions every 11-18 days [161]. Inflorescence is a spike. Flowers are pale blue or violet, displaying a yellow patch in the standard perianth lobe. The Pontederiaceae is one of the two monocotyledonous families (the other being Amarylladaceae) that display genetic polymorphism of tristyly, in which all flowers of an individual plant exhibit three distinct length of style and stamen. The "intermediate-style form" of water hyacinth is prevalent in its introduced range, whereas the "long- styled form" occurs less frequently. The "short-style forms" predominate in areas of native range in South America but have not been reported in its introduced range [165]. The success of this species is largely due to its reproductive output and can flower throughout the year and releases more than 3000 seeds per year [155,166]. While the seeds are long-lived, up to 20 years [155], germination takes place between 3 and 4 days [167].

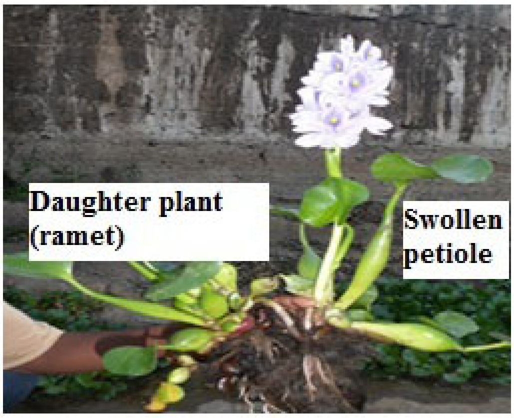

Fig. (12). *Eichhornia crassipes* habit - A parent plant with a daughter plant (ramet).

Uses: Water hyacinth is extensively grown in "waste water treatment and clean-up of polluted" environments [168, 169], and also in bio energy production [170]. Water hyacinth is also used in paper-making industry, in making ropes, floor mats, in biogas production *etc.*, in Indonesia and India [5, 6]. Water hyacinth has been found to be "rich in protein, vitamins and minerals and serves as a high quality feed stock used in poultry and fishery in Indonesia, China, the Philippines and Thailand" [171, 172]. However, "its high alkalinity and potentially toxic heavy metal contents would restrict its use as manure" [173, 174].

6.3. Historical Spread in Botswana

In Botswana, water hyacinth is not found in the inland waters. The weed was first noticed at the confluence of Marico and Crocodile Rivers of Olifants Drift of the trans-boundary Limpopo River (Fig. **14a**) between Botswana and South Africa in May 2010 and by 2014 it had spread through the entire legth of the Limpopo River. The main source of infestation to the river is Hartbeesport Dam on Crocodile River in South Africa. Water hyacinth proliferates well in stagnant waters of the small dams in the Limpopo River between Martins Drift and Zanzibar during the off-flood season from April to November. Between December and March of the flood season, the plants were washed away by the flash floods to the downstream all the way between South Africa and Zimbabwe and probably ended up in the Indian Ocean [175].

6.4. Negative Impacts - Limpopo River

Being the 'World's No. 1' aquatic weed, the negative impacts of water hyacinth on the aquatic systems are well known [15]. The notable impacts of water hyacinth in the Limpopo River are: "impacting socio-economic values including ecology, river navigation, water storage facilities, community fishing and infrastructure development". The weed was found clogging water pumps thereby affecting irrigation facilities/infrastructure [175].

6.5. Factors Affecting Growth

Neutral pH favors water hyacinth proliferation, although the plant can tolerate pH levels from 4 to 10. High light intensities and nutrient-rich water also encourage population build-up. Growth is directly correlated with nutrient concentrations [155] and higher nitrogen and phosphorus in waters increase biomass as well as favours the growth of thick stands [176, 177]. Optimal growth occurs at temperatures of 28-30°C, while growth ceases when water temperatures drop below 10°C. But prolonged "cold temperatures, below 5°C, result in death of the plants" [155]. Water hyacinth has taken the advantage of eutrophic aquatic systems with more than 1 mg L^{-1} phosphorus [159]. The pH is ranged from 6.5 to 8.5 with a range of 0.41 to 9.56, 0.2 to 2.9, and 7.7 to 11.53 mg L^{-1} of soluble nitrates, phosphates and potassium respectevily [175].

6.6. Management

6.6.1. Physical and Mechanical Control

Manual and mechanical removal may be applied depending on the intensity of infestation. In developing countries, manual removal with simple mechanical devices is still practiced [15] and it is labour intensive [178, 179]. Moreover, "the long-lived seeds germinate and reinfest sites soon after exposure to light as a consequence of physical and chemical removal of the plant" [161]. In Africa a manual-removal program followed by "bulldozer, a boat, a conveyor, and dump trucks" was initiated in Zimbabwe on Lake Chivero in the early 1980s [180]. Mechanical control was implemented around Port Bell and Owen Falls Dam on Lake Victoria but with limited success [181]. Malawi Aquatic Vegetation Control administration used weed harvesting Grab Crane in 2004 and Swamp Devil in 2005 in Lake Malawi with minimum control of water hyacinth [182]. Biological control integrated with manual and mechanical extraction of water hyacinth in Lake Victoria and Uganda resulted in more than 80% control but infestations remained un-tackled in riverine environment**.** Despite these problems, reasonably successful results were obtained in Mexico, where a combined chemical-mechanical program, using the herbicide 2, 4 -D and a triturator, was implemented to control water hyacinth on the Trigomil Dam [183].

6.6.2. Chemical/Herbicide Control

Herbicide control is effective only on small groups of water hyacinth infestations, which are accessible by land or boat, but is relatively expensive. Water hyacinth is susceptible to herbicides such as "2, 4-dichlorophenoxyacetic acid (2, 4-D), diquat, paraquat, glyphosate, anitrole [184], and they are successful in small irrigation canals and dams" [185].

In South Africa "a severe water hyacinth infestation on the Hartebeespoort Dam was brought under control using the terbutryn herbicide Clarosan 500FW" in the late 1970s [186]. The dam is "used for potable water, washing, and fishing, as such the use of chemical sprays contaminates these sites and threatens human health" [187]. Currently ecosystem approach is being implemented: using reed and other aquatic plants grown in the dam to try and suppress/control the proliferation of water hyacinth. However, Kilo Max 700 WSG, an organo-phosphoric acid herbicide (N-phosphono methyle) glycine {C6H17N2O5P}, recently introduced, has been found to be effective for water hyacinth control. Kilo Max, an eco-friendly herbicide, works both on plants that are rooted in mud and floating plants. It takes between 10-15 days for the plants to die and they then either sink or the material stays on the muddy banks (Pers. com. Water Affairs, South Africa).

6.6.3. Biological Control Agents

"Research into the biological control of water hyacinth was initiated by the United States Department of Agriculture (USADA) [119] in 1961, and the first control agents against the weed were released in Florida" [188]. Under ideal conditions of tropical areas, the speed and efficiency of biological control of *E. crassipes* can be expected in 3-5 years. Around the world, "seven arthropod agents" have been developed for the classical biological control of water hyacinth. They are: two weevils *Neochetina eichhorniae* Hustache and *Neochetina bruchi* Warner (Coleoptera: Curculionidae); three moths (*Bellura densa* (Walker) (Lepidoptera: Noctuidae), *Niphograpta albiguttalis* (Warren) (Lepidoptera: Pyralidae), and *Xubida infussella* (Walker) (Lepidoptera: Pyralidae)); a bug *Eccritotarsus catarinensis* (Carvalho) (Hemiptera: Miridae), and a mite *Orthogalumna terebrantis* Wallwork (Acarina: Galumnidae). Among these six agents "two weevils, *N. eichhorniae* and *N. bruchi*, are considered the most efficient" (Fig. **13**) [189, 190]. *Neochetina bruchi,N. eichhorniae*, *N. albiguttalis* and *X. infusella* have been notably established in Lake Chivero (Zimbabwe), Lake Victoria (Kenya), Lousiana (USA), Mexico, Papua New Guinea and Benin [14, 191]. The 8th agent, a plant hopper *Megamelus scutellaris* Berg (Hemiptera: Delphacidae) another biocontrol host specific agent identified from South America was released in Australia and approved for release in South Africa for biocontrol [192, 193]. Fungi species such as *Cercospora rodmanii* Conway and *C. piaropi* (Ascomycotina) (Fig. **13**) are capable of decreasing *E. crassipes* biomass [194, 195]. The other fungal pathogens include *Acremonium zonatum* (Sawada) W. Gams and *Alternaria eichhorniae* Nag Raj & Ponappa (Ascomycotina) also cause damage to water hyacinth. Several new agents have been under trial in some countries of the world including South Africa [15].

Neochetina species (Coleoptera: Curculionidae): Members of the genus *Neochetina* are semiaquatic weevils that feed only on species of Pontederiaceae. Adults of the two species are distinguished by the colour and pattern of the scales on the elytra [15, 196]. *Neochetina bruchi* is typically brown with a tan band across the elytra and *Neochetina eichhorniae* is usually mottled grey and brown. Both species have two parallel tubercles on the elytra on either side of the mid-line, which are short on *N. bruchi*, but are longer on *N. eichhorniae*. Larvae are 8 to 9 mm, can be distinguished by the presence (*N. bruchi*) or absence (*N. eichhorniae*) of "setal-bearing protuberences on the pedal lobes" [15]. *Neochetina bruchi* supplements the damage caused by *N. eichhorniae* and is an important weevil in eutrophic water bodies. *Neochetina eichhorniae* lives for ±120 days and *N. bruchi* lives for ±95 days.

Feeding habits: The weevils reduce water hyacinth vigor by decreasing plant size, vegetative reproduction, and flower and seed production [15]. Adult weevils feed on the epidermis and mesophyll tissue of the leaves, larvae tunnel through the petiole and browse meristematic tissue in the crown of the plant causing significant damage [197]. Both species can produce up to three generations per year in their native range [189, 198], but temperature and plant nutrient status influence generation time in their introduced ranges, and thus the level of control differs. The optimal temperature for feeding and oviposition is approximately 30° C and will not hatch at temperatures below 20°C.

Niphograpta albiguttalis (Lepidoptera: Pyralidae): The five larval instars of the moth *N. albiguttalis* inflict damage by tunneling within the petioles, damaging the growth meristems, but damage is not usually inflicted to the crown base. Adult longevity ranges from 4 to 9 days, and up to five generations per year are produced. Adult moths prefer smaller plants, with inflated (bulbous) leaf petioles [199].

Method of Control: Petiole damage "hinders the ability of the plant to stay afloat, and the translocation of nutrients is reduced, adversely affecting the nutrient dynamics of the plant" [15, 190]. As a result of tunneling by larvae in the crown and in the lower petioles, water enters the plants causing waterlogging, which encourages invasion by secondary fungi that rot tissues, contributing to the death of the plant and eventual sinking [15].

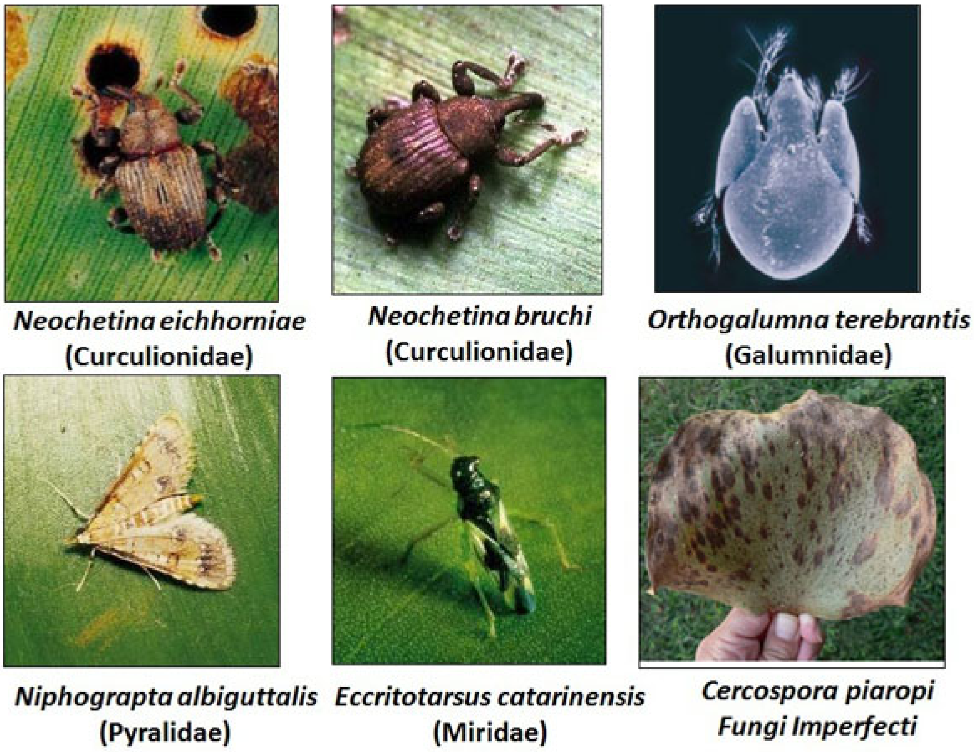

Fig. (13). Biocontrol agents of *Eichhornia crassipes* (Source. M. P. Hill, Rhodes University, South Africa).

Success of water hyacinth control: The success of water hyacinth control is reported to be varied in the released countries unlike in the case of 'salvinia weevil' *C. salviniae* that controls *S. molesta* quite effectively and efficiently [11]. However, satisfactory control has been achieved for water hyacinth using *Neochetina* species, along with *N. albiguttalis* in some of the countries. The *Neochetina* spp. and *N.albiguttalis* have been in use in North America, Africa and Asia [84]. The control of water hyacinth depends on the age of the plants, habitat, flooding, climatic conditions and nutrients especially nitrates and phosphates. "Biocontrol has been successful in tropical countries such as Papua New Guinea [200], Malawi [201], Lake Victoria [202, 203], where only *N. eichhorniae* and *N. bruchi* were released" [15]. In Benin control by *N. eichhorniae* was substantial but not satisfactory [204, 205]. On the other hand, five arthropod and one pathogen species of control agents have been released in South Africa and satisfactory results have yet to be achieved [206]. Even though biocontrol agents have been released in south of China [158, 207], India [157], Mexico [208], the southern USA, and some parts of Australia, control has not been at expected rates [15].

6.6.4. Management - Botswana

Soon after the observation of water hyacinth plants floating from Crocodile River to the trans- boundary Limpopo River, the DWA Botswana, alerted the Department of Environmental Affairs (DEA)**,** South Africa about the threat of the weed for the river. Workshops organized jointly by Botswana and South Africa in November 2010 and July 2013 resolved to develop joint strategies to tackle the water hyacinth in the river with emphasis to develop management plans at the source point, Hartbeesport Dam. As a maiden management program, South Africa conducted a helicopter survey jointly with Botswana in September 2012. The survey revealed that there were thick patches of the weed stretching for about 25 to 30 km from Martins Drift up to Seleka Farms and beyond. The dense plant infestations were physically removed at Olifants Drift and at water drawing points between Martins Drift and Zanzibar from 2012 to 2014 (Fig. **14a**) [175].

Botswana undertook extensive ground survey in September 2013 from Zanzibar to Olifants Drift and collected the coordinates using GPS to map the intensity and scale of water hyacinth infestations with an aim to focus on the application of integrated control management. This facilitates the harmonization of the two countries' institutional mechanism with the support of stakeholders contributing to regional knowledge, management processes, for efficient use of water resources across borders.

Marico and Limpopo Rivers and the inflow rivers into the Limpopo Basin were digitalized using aerial photographs (Fig. **14a**). The Limpopo River has been divided into 46 sections on the basis of the presence of weirs or dams across the river. The area of water hyacinth has been determined using Arc Map 10 as 0.201 km^2 occupying *ca*. 325 tons by fresh weight. About 14 areas of back water bodies and side channels have been found to be suitable for the introduction of biocontrol agents, *N. eichhorniae* and *N. bruchi.* Water hyacinth in the main river either was manually removed or sprayed by the chemical Kilomax, using back-pack spray operations followed by the application of physical control methods.

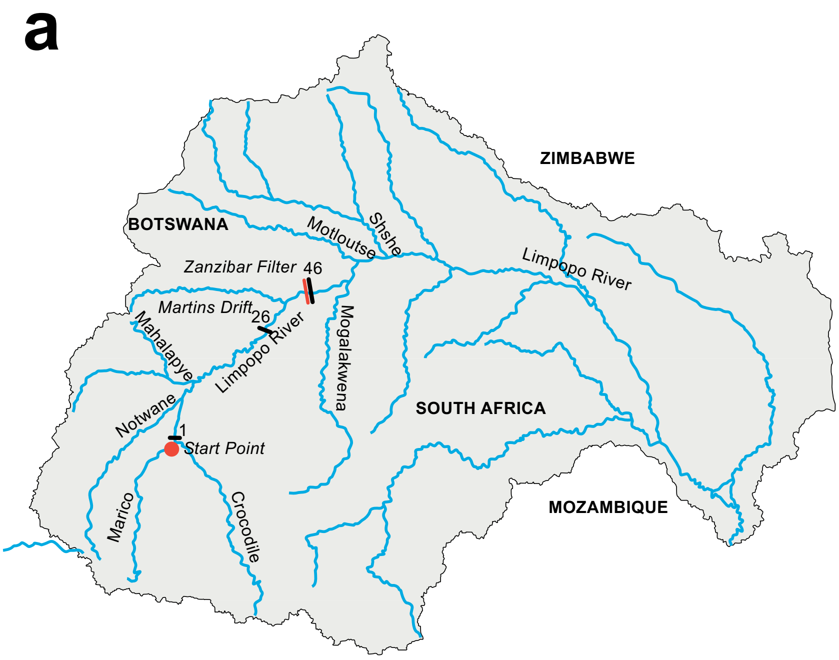

Fig. (14a). Limpopo Basin with the Limpopo River and other inflow rivers. Infestation of *Eichhornia crassipes* from 'Start Point' in Marico River and up to 'Zanzibar Filter' on Limpopo River. The infestation of *E. crassipes* is divided into two major sections from 1 (Start Point = Olifants Drift) to Martins Drift (26) and from Martins Drift to Zanzibar Filter (46). The 1st section has 23 weirs/dams and the 2nd section has 20 weirs/dams.

Fig. (14b). Plants trapped at the Zanzibar filter for physical removal.

As the downstream is mostly seasonal, a diamond mesh filter across the river was installed using two steel wires ropes at Zanzibar (Fig. **14b**) in February 2013 to prevent the floating of plants downstream. About 2 tons of plant material was removed in 2013 flood season. The filter was disconnected in 2014 flood season as a result of immense water hyacinth mat floating and clogging at the filter. Physical removal of plants is extremely difficult to apply in the flash flood rivers [175]. The entire water hyacinth infestation in Limpopo River from Oilfants Drift to Zanzibar was washed away by the flash floods of February 2014 to the tail end of the river in Mozambique and finally reached the Indian Ocean.

7. AIS MANAGEMENT - STAKEHOLDER PARTICIPATION

Through the 'Biokavango Project' implemented (2008-2011) by the Okavango Research Institute, Botswana, the Aquatic Unit in the Department of Water Affairs selected four tourist lodges as Champion Sites in the Moremi Game Reserve of the Delta to monitor and control salvinia in their concession areas of operation. The Unit trained tourist guides in the lodges to monitor and control salvinia within their areas of operation as a continuous capacity building program. Weevil breeding portable pools were provided to the lodges to rear salvinia weevils for their release in the concession areas. This is a successful initiative in the conservation of wetlands in collaboration with the tourism sector. Through these experiences, the DWA has replicated the project with a community tourist lodge run by Sankuyu Trust. The Shorobe Trust in Maun participated in the salvinia integrated control program for its successful control in one of the distal stream areas of the Okavango Delta. Safari lodges on Khwai River and Selinda Canal on Kwando River and few NGOs have been part of the collaboration with the Department of Water Affairs for salvinia control management. Farmers along the Limpopo River have already formed a surveillance program on water hyacinth, which provides significant input in its spread and management. The department has established initiatives in the weed control program with Kalahari Conservation Society of Botswana.

8. LEGISLATIVE CONTROL

The Government of Botswana gazetted the Aquatic Weed (Control) Act in 1971 and implemented it on 24th October 1986 [209]. The "Act regulates the Inspection, Movement and Importation of boats and aquatic apparatus, and fishing gear, to prevent the importation and spread of aquatic weeds". The government specifies inspection and disinfection procedures for boats and aquatic apparatus and they are checked and/or treated before passing between any of the six declared zones (Fig. **15**). The salient features of the Act described in Chapter 34:04 are summarized below.

a). Based on the surface waters and the presence of dams, the country has been divided into six zones viz., Okavango Zone-OK, Kwando-Linyanti Zone -KL, Chobe Zone-CH, Nata- Sua Zone-NS, Limpopo Zone-LP and Marico Zone-MR (Fig. **15**).

b). Inter zonal movement permits for the boats and aquatic apparatus must be obtained from the Department of Water Affairs situated in their respective zones.

c). Import for boats from outside the country should carry import permits, which may be obtained from the Department of Water Affairs, Gaborone and Maun.

d). Traditional wooden Mokoros are exempted from registration.

e). Any person found with a boat without import permit, registration number, interzonal movement permit, herbicide treatment, shall be guilty and upon conviction be "liable to a fine of US$100.00 and/or imprisonment for 12 months or to both".

f). No person shall import into Botswana, or move within Botswana in possession of the weeds listed in Table **8** including any other aquatic weeds; if found," shall be guilty of an offense and liable to a fine not exceeding US$200.00 or to a imprisonment for a term not exceeding two years or to both.

g). Any person who brings boats carrying other country registration and aquatic apparatus "shall be guilty of an offence and on conviction thereof shall be liable to a fine of not exceeding US$50 or to imprisonment for a term not exceeding six months, or to both".

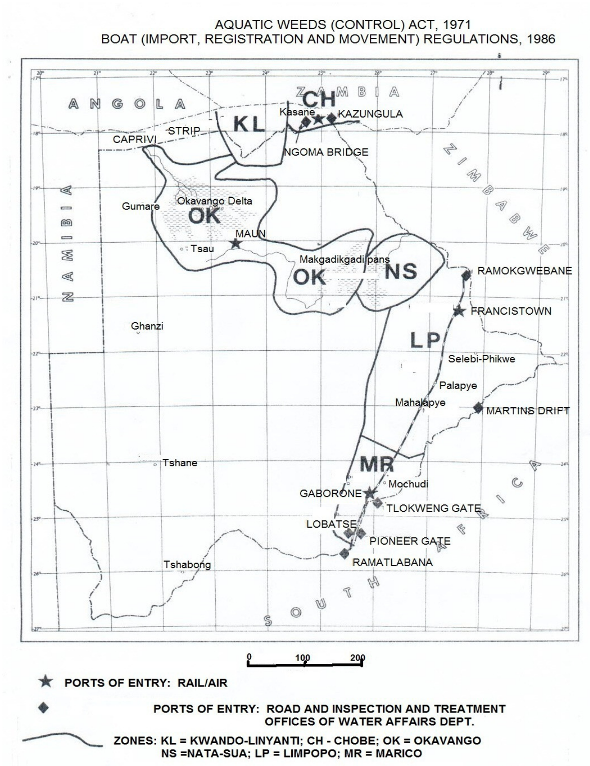

Fig. (15). Botswana's six (06) Zones for monitoring Boat movement

Table 8. Aquatic invasive plant species prohibited for entry from outside and movement within Botswana [Aquatic Weed (Control) Act 1986].

Scientific (Botanical) Name	Family	Common Name
Eichhornia crassipes (Martius) Solms-Laubach	Pontederiaceae	Water hyacinth, Nile lily
Salvinia molesta Mitchell	Salviniaceae	Kariba weed, Motshimbaa
Pistia stratiotes L.	Araceae	Water lettuce, Nile cabbage
Azolla filiculoides Lamarck.	Azollaceae	Red water fern
Myriophyllum aquaticum (vell.) Verdc.	Haloragaceae	Parrot feather
Elodea Canadensis Michx	Hydrocharitaceae	Canadian water weed
Hydrilla verticillata (L.F.) Royle	Hydrocharitaceae	Water thyme
Egeria densa Planch	Hydrocharitaceae	Dense water weed

9. COST AND BENEFIT ANALYSIS

Control of weeds involves two economic cost analyses: a) economic cost for the control of the weed and b) environmental damages caused by weed infestations. Environmental damages may be difficult to assess while economic costs for the monitoring and control of weeds by physical, herbicidal, mechanical and biological applications vary with the intensity of infestation of a species and from year to year. In the cost benefit analysis, factors such as the type of control applied and length of time are to be considered. Complete control of any weed is reached when populations are reduced below an ecologically and economically viable threshold, and are maintained at that threshold with no requirement of an additional intervention. Biological control is considered the most cost-effective method, but it varies from species to species. For instance *S. molesta* can be controlled in a year. *P. stratiotes* 1 to 2 years and *E. crassipes* takes 3 to 5 years as compared with chemical and physical control. The combined costs of the biological control projects was approx. Au$ 5 million in 1974-1993 and for *E. crassipes* project, the cost was Au$ 636 000 in the period of 1974-1991 [210]. Substantial economic losses were estimated at US$ 120 billion annually in USA for aquatic weed control programs [211]. In South Africa, "estimated economic costs due to invasive alien species are currently above US$ 620 million per annum" and could rise further [212]. The Government of Botswana spent approximately US$ 175,000.00 annually. This includes pay, subsistence, overtimes and casual labour costs for the monitoring and control of alien invasive species in the country. The movement of tourists to Dombo, Oyi, Xini and other areas of the Delta was affected and incurred a considerable loss for tourism between 1992 and 2010.

10. Public Awareness Program

The "Aquatic Vegetation Control Unit in the Department of Water Affairs" undertakes public awareness programs on annual basis. The program includes distribution of posters depicting the weeds and their impacts to water systems. Notices about weed plants and their impacts to the aquatic systems are issued at border posts and National Park entry points. Safari operators are consulted to disseminate information to their inmates. Regular Kgotla meetings are held to sensitize communities about the danger of alien invasive species. Sign boards have been erected and maintained at important Road Check Points and Ports of Entry at the borders to inspect boat permits, registration and boat spraying documents. In South Africa, a single DNA barcode (trnH-psbA) was developed for freshwater plant species identification to find out the prohibited aquatic invaders that are in circulation in the local aquarium trade as well as to check their transportation at the port of entries [213]. This calls for strict regulation of alien species in aquarium trade through public environmental education.

CONCLUSION

Biological control using *C. salviniae* for *S. molesta* is very effective and less costly in several countries including Botswana. However, precautions have to be taken for its control in winter months of May to July as the weevil population is reported to decline. Water lettuce is not considered a weed of high importance in the country and it had been under control biologically in the Chobe River. For *E. crassipes* herbicide control using Kilomax has been resolved to apply as a temporary measure jointly with South Africa. This exercise could be followed with the application of physical and biological control by introducing *N. eichhorniae* and *N. bruchi*.

Weed science has shifted its emphasis from herbicide science to a discipline that focuses on eco-friendly practices on weed management as well as to exchange information between researchers and stakeholders [214]. The studies undertaken in natural and semi-natural environments provide new tools and knowledge in support of preventive measures and integrated control of weeds. Increased stakeholder participation in widening the scope of research efforts on weed control programs to include social sciences, law and economics should be encouraged. Disseminating information about the causes and impacts of biological invasions will help support efforts to reduce the spread of invasive species. Communities, conservation groups, NGOs and agencies should undertake prevention and management activities and have easy access to science-based biological and ecological information about target species. Government of Botswana through the Department of Water Affairs has mechanisms in exchanging invasive species information with Conservation of Biological Diversity (CBD) and IUCN Invasive Species Specialist Group (ISSG) Secretariat. Climate change could impact some water bodies currently vulnerable to invasion by weeds to become resilient while others that are currently resilient may become vulnerable for weed invasion [215]. Therefore, weed control managers are to be vigilent about the climate change in relation to weed spread.

CONFLICT OF INTEREST

The authors confirm that this article content has no conflict of interest.

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The authors acknowledge the internet websites notably "www.el.erdc.usac.army.mil; www.eppo.org; www.fs.fed.us; www.unep.org; www.invasive.org; www.cbd.int; www.apms.org; www.aquaticinvasions.ru" on weed management browsed during the preparation of this review.

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