Environmental and human facets of the waterweed proliferation in a Vast Tropical Ramsar Wetland- Vembanad Lake System

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Abstract

The Vembanad Lake and its associated low-lying areas and network of canals (hereafter VBL) form the major part of India's second-largest Ramsar wetland (1512 km^2). Located in Kerala State on India's southwest coast, the extensive VBL has a large fishery, inland waterways, and popular tourist attractions that support the livelihoods of thousands of people. Over the last several decades, the proliferation of water weeds in the VBL has alarmingly increased, causing many adverse ecological and socioeconomic effects. *Eichhornia crassipes*, *Monochoria vaginalis*, *Salvinia molesta*, *Limnocharis flava*, *Pistia stratiotes*, and *Hydrilla verticillata* are the most troublesome water weeds in the VBL, with the first three being the most widespread. They were mostly imported to India long ago before becoming a part of the VBL. These weeds harmed water quality, waterways, agriculture, fisheries, disease vector management, as well as the vertical and horizontal shrinkage of the VBL through increased siltation and faster ecological succession. The inherently fragile VBL was harmed by extensive and long-term reclamation, the construction of saltwater barrages, and many landfill roads that crisscross water bodies serving as coastal dams, creating water stagnation. These ecological imbalances were exacerbated by excessive fertiliser use in agricultural areas, as well as the addition of nutrient-rich domestic and municipal sewage, which provided an adequate supply of nutrients and a favourable habitat for the expansion of water weeds. The recurrent floods in the VBL also favour the proliferation of water weeds, with the potential to disrupt their current distribution pattern and spread in the future.

1. Introduction

A wetland is an area of land covered by water, such as ponds, marshes, the edge of a lake or ocean, estuaries, river mouth deltas, and low-lying flood plains that support both aquatic and terrestrial life. It is a critically important area for the environment as well as a productive and valuable public resource, and its needless modification or destruction is discouraged worldwide to safeguard the public interest (National Research Council, 1995; WISA, 2013). Kerala State, located in the southwestern part of the Indian subcontinent, has a massive network of water bodies that run parallel to its 590 km coastline. From south to north, these water bodies are Veli, Kadinamkulam, Paravoor, Ashtamudi, Kayamkulam, Vembanad, Kodungalloor, Valiyangadi, Korapuzha, Valiyapatnam, and Kavvai (Gopalan et al.,1983). The VBL, located in the south-central part of Kerala State, encompasses the major part of the Vembanad-Kol wetland, India's largest Ramsar wetland of 1512 km^2 (Gopalan et al.,1983; Jyothibabu et al., 2006; 2015). VBL has two inlets to the neighbouring Southeastern Arabian Sea (SEAS), one slightly broader (500 m) in Kochi than the one in Munambam/Azhekkodu (165 m), both located in the north-central section of VBL and separated by around 40 km alongshore. VBL has estuarine zones, brackish water, mangroves, swamps, lagoons, rice fields, and an incredibly enormous and complicated network of canals and river basins (Fig. 1; Revichandran et al, 2012, WISA, 2013; Haldar et al., 2019).

The VBL was a marine embayment long ago during the Pre-Holocene (11,650 years ago) and subsequent geomorphic processes formed its current shape (Gopalan et al., 1983; Mallik and Suchindan, 1984; Padmalal et al., 2014; Sreejith, 2013; WISA, 2013). The abundant fossilised marine molluscs excavated in the subsurface soil in the VBL as well as on the adjacent land are direct evidence of its marine origin (Narayana et al., 2002; Padmalal et al., 2014; Kaladharan et al., 2017). The VBL can be considered into three sections: northern, central, and southern, and it is separated from the adjacent SEAS by a strip of land formed primarily of alluvium and sand deposited by six major adjoining rivers: one in the north (River Periyar), one in the centre (River Muvattupuzha), and four in the south (Rivers Achancoil, Pamba, and Manimala, Meenachil) (Gopalan et al., 1983; Jyothibabu et al., 2006; 2015; Sreejith, 2013). Because the northern and central sections of VBL are near the inlets, they are more exposed to saline intrusion from the SEAS. The northern section around Kochi (Cochin) and the southern sector around Alappuzha (Alleppey) are the two largest urbanised areas along the VBL's banks. In addition, various townships are located in the vicinity of the southern sector of VBL, such as Kottayam, Changanacherry, Thiruvalla, and Chengannur (Fig. 1). The Kuttanad region is located in the southern sector of the VBL around Alappuzha and is notable for its vast rice (paddy) fields and peculiar topographical features. It has India's lowest elevation and is one of the few sites in the entire world where below-sea-level farming is practised (at 1.2 to 3 metres below MSL) (Gopalan et al., 1983; Balchand et al., 1983; Sreejith, 2013; WISA, 2013). The main sources of water in the Kuttanad are four rivers (Manimala, Meenachil, Pampa, and Achenkoil), among which Pampa and Achenkoil flow in a weblike pattern from Veeyapuram, 35 kilometres south of Alappuzha, which is known as the ‘Venice of the East’ because of its numerous interlinked canals and lakes. The nutrient-rich alluvium deposited in VBL each year as a result of seasonal flooding of these four rivers during the Southwest Monsoon [(SWM) (June-September)] is the economic backbone of the Kuttanad region, nourishing the extensive paddy cultivation fields there (Gopalan et al., 1983; Balchand, 1983; Dinesh Kumar, 1997; Sreejith, 2013; WISA, 2013). Kol fields (local name: Kari Nilangal) may be found in Vaikom and Purakkad in Kuttanad, in addition to those in the Trichur district of Kerala State, which is considerably northeast of the current research region of VBL. All these three Kol fields, along with the VBL, are generally referred to as the Vembanad-Kol wet lands, which is a slightly larger geographical domain than what is considered in this study (Gopalan et al., 1983; WISA, 2013).

The adjacent SEAS has mixed semidiurnal tides (two highs and two lows per day), which provide a regular tidal ingress and egress into the VBL through the Kochi and Munambam inlets, allowing its frequent ventilation and flushing (Gopalan et al., 1983; Revichandran et al, 2012). The Western Ghats mountain range, which runs parallel to India's southwest coast, is the eastern boundary of Kerala State and facilitates the VBL's watersheds and river basins, being located on a steeper plain, allowing for a swift flow of water in these rivers, which also release a large amount of freshwater and sediments into the VBL, especially during the SWM, when 70% of its annual rainfall occurs in the study domain (Fig. 2), converting the entire VBL into a massive freshwater lake (Gopalan et al., 1983; Madhuprathap et al., 1987; Balachandran, et al., 2005; Jyothibabu et al., 2006; 2015). Because of the enormous seasonal changes in the freshwater influx into VBL, its flushing time varies substantially over seasons, with roughly 7 days during the SWM and 70 days during the Pre-SWM (John et al., 2020). The northern sector of the VBL, which includes the River Periyar and its surrounding areas, is a densely populated, semi-urbanized area with numerous industries (Gopalan et al., 1983; Joy et al., 1990; WISA, 2013). Industrial pollution in this region and the associated societal issues have been a topic of great concern since the inception of the numerous factories on the bank of the River Periyar (Gopalan et al., 1983; Joy et al., 1990; Balachandran, et al., 2005; WISA, 2013).

Invasive aquatic plants grow in water, either partially or completely, which includes those that are rooted in the sediment with part or all of the plant underwater, as well as plants that float freely without contacting the sediment (Anderson, 2011; Jayan and Sathyanathan, 2012). They can invade both marine and freshwater environments, including wetlands, lakes, rivers, estuaries, coastal zones, irrigation systems, hydroelectric systems, and aquaculture facilities (Anderson 2011). A more generic term, "water weeds," is used in this study to collectively represent the aquatic plants dealt with in this study, as they cause many adverse effects on the environment (Lancar and Krake, 2002). The proliferation of waterweeds in VBL is currently posing an alarming ecological and socioeconomic challenge (Supplementary Material 1). The local community's concerns, particularly in the Kuttanad, frequently receive print and visual media attention, and India’s National Daily 'The Hindu' reported on February 2, 2019, that "almost 95% of the water bodies in the Kuttanad of VBL are infested with water weeds, and it has reached serious proportions, necessitating urgent measures to contain the infestation (Supplementary Material 2). Even more disgusting is to realise that most of the currently proliferating weeds in VBL were introduced by men for commercial interests many decades ago (Gopalan et al., 1983; Jayan and Sathyanathan, 2012). Given the foregoing context, the objectives of the study are as follows: (a) to provide a comprehensive review and synthesis of the ecological causes and consequences of water weed proliferation in the VBL; (b) to contextualise long-term changes in the VBL's natural hydrographic environment and how they favour the current proliferation of water weeds; and (c) to create a historical outline of water weed proliferation in the VBL and evaluate how human activities at present favour their expansion; and (d) to discuss the complex aspects of managing these weeds in the VBL in the context of changing the environmental regime, expanding human settlements, and periodic enhanced flooding in the region.

2. Methods

This study was primarily based on a review resulting from a thorough and systematic search of the literature to reduce selection bias. To meet the objectives, information from authoritative publications and project reports were gathered and summarised under various subtitles. Schematic figures and tables were used to ensure that facts and concepts were fully understood. In addition, extensive field visits have been conducted in the VLS in October 2021 (Post- SWM) to capture photographs evidencing the alarming water weed proliferation in different sections of the system. These photographs were georeferenced and are shown in Fig. 1 using the QGis software. Given the scarcity of information on nutrient concentrations in water weed-infested areas, water samples were collected using 5 litre Niskin bottles from a range of different sections of the VLS where water weeds were abundant. The water samples were transported to the lab and stored in a refrigerator and used for analysing the nutrients (nitrate and phosphate) following the standard procedures (Grasshoff, 1983). Satellite-derived monthly average data of rainfall is downloaded from the online data source (giovanni.gsfc.nasa.gov) and plotted for Kerala and the adjacent South-Eastern Arabian Sea. The influence of the hydrological barrage on VBL is envisaged by plotting vertical salinity characteristics before and after the construction of the Thanneermukkom Bund. Salinity data were obtained from Haridas et al., (1973) and Arunpandi et al., (2021) to represent the salinity distribution in the VLS before and after the barrage, respectively, to gain an understanding of the long-term change in the salinity distribution. A satellite image of VBL before and after the flood event of August 2018 was obtained from NASA Earth Observatory (https://earthobservatory.nasa.gov/) to visualise the extent of flood water inundation in the VLS favouring the spread of water weed proliferation

3. Dominant Water Weeds In Vbl

Water weeds have significantly expanded their geographical extent in the VBL during the last five decades as a result of a variety of environmental and human factors (Balchand,1983; Dinesh Kumar, 1997; Jayan and Sathyanathan, 2012; Arunpandi et al., 2021a,b). The hydrographical settings that facilitate the proliferation of water weeds in VBL have developed over many decades, some of them initiated even before the introduction of these weeds into VBL, which is a clear case of the adverse implications of the unscientific management of sensitive wetlands for various human needs. The most troublesome water weeds in the VBL now are *Eichhornia crassipes* (hereafter *Eichhornia*), *Monochoria vaginalis* (hereafter *Monochoria*), *Salvinia molesta* (hereafter *Salvinia*), *Limnocharis flava* (hereafter *Limnocharis*), *Pistia stratiotes* (hereafter *Pistia*), and *Hydrilla verticillata* (hereafter *Hydrilla*), with the first three being the most widespread (Figs. 3 & 4). Although the precise year of their invasion into the VBL is unknown, *Eichhornia*, *Salvinia*, and *Limnocharis* are obvious alien bioinvaders. Except for *Salvinia*, all these water weeds were not recorded in 1970s studies on the environmental status of the VBL immediately following the commissioning of the Thannermukkom saltwater barrage (Kannan, 1979; Balchand, 1983), implying that the proliferation of all of them in the VBL most likely began in the 1980s (Gopalan et al., 1983; Balchand, 1983). Globally, many transportation channels are proposed for the introduction of alien plants into new habitats, including ballast tanks, airline cargo, rivers, the nursery and the aquarium trade, all of which are examples of artificial vectors that contribute to the spread of bioinvaders (Colautti et al., 2004; Cohen et al. 2007; Imchen et al., 2018).

Eichhornia (local name Kulavazha, Pola) is a Brazilian 'floating' invader that was introduced to India long ago for its aesthetic appeal (Fig. 3A), and it was first introduced in the late 1890s in West Bengal (Naidu et al., 2014; Kumar, 2015). It is uncertain when *Eichhornia* was introduced into the VBL, but it is now the most hazardous and dominant water weed, and its capacity to form dense mat-like colonies has hampered irrigation, agriculture, fishing, inland traffic, and tourism in the region. *Eichhornia* contributes predominantly to the huge floating weed biomass advected with water currents, a sight prevalent in all sections of the VBL, especially during the SWM. *Monochoria* (local names: 'Kakkapola,' 'Karimkovalum,' and 'Kolachempu') is an emergent invader in the VBL with common names 'oval-leafed pondweed' or 'heartleaf false pickerelweed', although it hasn't received nearly as much scientific attention as *Eichhornia* (Fig. 3B). However, because of the semi-aquatic characteristics of *Monochoria*, it has grown increasingly prevalent in interior canals, shallow and stagnant water bodies, and rice fields in the VBL (Athira et al., 2019). *Monochoria*, unlike *Eichhornia*, has long, inflexible stalks and bigger leaves that make navigation, fishing, agriculture, and tourism exceedingly difficult. They attach to the bottom sediments due to their large size, intensive colony development, and powerful root anchoring, making navigation in their infested zones impossible. Because of its irregular germination, rapid growth, and remarkable adaptability (Athira et al., 2019), *Monochoria* is often gregarious and competitive, with its origins considered to be in Asia and Western Australia (Waterhouse, 1994; Li et al, 2021). Considering the "semi-aquatic" behaviour of *Monochoria*, it appears that its increasing spread and dominance in many sections of the VBL may be a biological indication that these places are on the verge of becoming swamps. *Salvinia* (local name ‘African payal’), also known as ‘Kariba weed' or ‘water moss’, is a ‘floating' invader from Brazil that was introduced into VBL in the 1950s (Fig. 3C) (Cook and Gut 1971; Forno and Bourne, 1985; Arunachalam et al., 1980; Balchand, 1983; Thomas and Room, 1986). It is a widespread and dominant weed in many parts of VBL, posing a threat to local flora and fauna as well as causing difficulties in navigation, fishing, agriculture, and other human livelihood activities (Thomas, 1962; Joy, 1978; Kumar, 2015). *Salvinia* competes even with *Eichhornia*, the most widespread invasive water weed in VBL, and even outnumbers them in many places (Thomas, 1977, 1979).

Pistia is a ‘floating' water weed (local names: ‘Akasathamara’, ‘Angillapongu’, ‘Kudappayal’, ‘Muttapayal’, ‘Neercheera’) that is also known as ‘water lettuce’, ‘Nile cabbage’, ‘shellflower’, or ‘water bonnets’ (Fig. 4A). It was initially discovered in Africa along the Nile, which is currently found in nearly all tropical and subtropical regions either naturally or as a result of human introduction, which facilitates conducive mosquito breeding habitat (Burton, 1959; Lounibos and Escher, 1985; Connelly,2019). *Hydrilla* is a ‘submerged' weed that is endemic to Asia, Africa, and Australia and has dense branches that reach the water surface (Fig. 4B). The leaves are strap-shaped and grow in whorls of 4 to 8 around the stem, with pointy tips and saw-tooth margins. In comparison to many other freshwater aquatic plants, *Hydrilla* has great resilience to salinity and can produce allelopathic chemicals that hinder the growth of many co-existing species in the natural environment. *Hydrilla* crowds out native plants by shading them and out-competing them for nutrients, and the dense masses it creates frequently hinder recreational activities such as boating, fishing, and swimming. *Limnocharis* is an ‘emergent weed' (local names: ‘Manja payal' and ‘Nagapola') that is generally known as ‘yellow velvetleaf/sawah flower rush/sawah lettuce' and was spotted in the rice fields of Kuttanad in the 1960s (Fig. 4C; Ramachandran 1961, Abhilash, 2004; Abhilash et al., 2008). It was introduced as a decorative plant but quickly turned into a noxious one, in rice fields, canals, lakes, and ponds (Nishan and George 2018). Also generally believed that *Limnocharis* seeds were mistakenly introduced into Kerala in the 1930s from Southeast Asian countries (Nishan and George 2018). In some regions of the VBL, *Limnocharis* even outrun *Salvinia*, one of the fastest-growing water weeds (Abhilash et al., 2008). The presence of several of these waterweeds in combination with native species is a common sight in many sections of the VBL since all of them have numerous advantageous characteristics that allow them to explore the many niches available in the habitat through their adaptive capacities. During their coexistence, these species may compete with one another, and over time, the fittest in the habitat may take over dominance by completely outcompeting other competitors, which alters the natural ecology of the system that has evolved (Garry et al., 1997; Mormul et al., 2012; Aloo et al., 2013).

4. Major Factors Favouring The Water Weeds

4.1. Sturdy survival characteristics

The dominating water weeds in the VBL have various advantages over native species, including the ability to endure a wide variety of environmental conditions and a generalist distribution pattern (Daehler, 2003; Forrest Meekins and McCarthy, 2001, Jakobs et al., 2004). They have superior reproduction strategies as well as effective dispersion mechanisms (Reddy 1984, Li, 2014, Bajwa et al, 2016). Furthermore, advantageous survival characteristics such as quick growth, high phenotypic plasticity, long seed dormancy, a deep and extensive root system that absorbs the most nutrients, and low grazing pressure provide them with an edge when competing with native flora (Newsome and Noble, 1986; Rotherham, 1990; Richards et al., 2006; Di-Nino et al., 2007). Natural enemies and predators keep these invasive weeds under check in their native habitats, but they escape their natural foes in unfamiliar situations, allowing them to grow fast (Van Driesche and Bellows, 1996). Most water weeds employ several reproductive strategies and exhibit discontinuous germination, wherein seeds and other structures have varied dormancy mechanisms that prevent all new plants from sprouting at the same time. *Eichhornia* has developed strategies for storing excess nitrogen and phosphate in modified petioles (Penfound and Earle, 1948), allowing them to thrive when nutrients in their environment are scarce (Gossett and Norris 1971).

Eichhornia reproduces both vegetatively and sexually, and their seeds can last for at least 20 years, making it almost impossible to irradicate them from natural open systems using usual approaches (Tellez et al., 2008; Patel, 2012). *Monochoria* is considered the most productive of all aquatic macrophytes because they use all three possible states for their survival-their roots in sediments, stalk beneath the water, and their photosynthetic portions in the air, which reproduce primarily through seed, with tubers providing occasional new growth (Westlake, 1963). Even though Salvinia does not reproduce sexually, its rapid vegetative growth makes it a successful invader; in fact, it is one of the world's fastest-growing water weeds, capable of doubling its biomass in less than 10 days (Blackman, 1961; Abbasi and Nipaney, 1986). The ability of *Limnocharis flava* to produce a large number of seeds (1,000,000 seeds per plant) combined with favourable climatic conditions makes them a hazardous alien invasion in many parts of the world (Karthigeyan et al., 2004). Changes in hydrology, such as flooding, efficiently distribute *Limnocharis* seeds. The fruiting capsules break quickly in the water, and some survive intact for a few days, allowing the seed to disseminate from the parent plant. It is most likely the seed that will be distributed by mud attached to boots, cars, machinery, animals, and birds (Nishan and George, 2018a,b). *Hydrilla* can reproduce asexually as well as sexually though the asexual plant fragmentation is their more typical dispersal mode. Their submerged tubers pose a serious problem as they can lie dormant for several years, making it extremely difficult to irradicate from waterbodies. *Hydrilla* also has a good resilience to saltwater, and it can also produce allelopathic compounds that restrict the growth of co-existing species in their habitat (Kulshreshtha and Gopal, 1983).

4.2. Upset of the hydrography, increased stagnancy and eutrophication

A pronounced seasonality exists in the amount of freshwater reaching into the VBL, most of which occurs during the SWM when the region receives more than 70% of its annual rainfall (Fig. 2; Qasim, 2003; Jyothibabu et al., 2006; 2015; Arunpandi et al., 2021 a,b). Thus, the entire VBL has freshwater dominant hydrography during the SWM, but during the rest of the period, it has a saltwater dominance in its downstream northern and central sections (Qasim, 2003; Jyothibabu et al., 2006). Many barriers/bunds have been built in the VBL over the years to prevent salt water intrusion into the upstream interior water bodies, among which the Thannermukkom Barrage (TB) in the southern sector is a massive engineering structure (Fig. 1; Supplementary Material 3). The other two prominent barriers are at the Pathalam and Manjummel, both in the northern sector of the VBL (Fig. 1; Supplementary Material 3). It was noted across the world that the saltwater barriers have an adverse ecological impact, as they create isolated and stagnant sections of water bodies, which accumulate nutrients and other pollutants (Kumar, 2011). Over many decades, the degradation of the VBL was caused largely by the flow restrictions of these vast barrages, spillways, and numerous landfilled roads all of which, in one way or the other, eventually favoured water stagnation and eutrophication (Kannan, 1979; Gopalan et al., 1983; Balchand, 1983; WISA, 2013). Numerous non-point nutrient loadings are quite common in the VBL associated with agriculture, municipal and domestic sewages, which results in a eutrophicated water column regardless of seasons (Balachandran, et al., 2005; Jyothibabu et al., 2006; 2015; Madhu et al., 2010; Ramani et al., 2010; Martin et al., 2008; 2010; 2011; 2012), and an updated long-term trend is shown in Fig. 5a. Similarly, the concentration of the nitrate and phosphate measured from the water weed proliferation regions in the VBL is presented in Fig. 5b, which evidences the widespread eutrophication prevailing in the VBL as observed in many earlier studies (Balachandran, et al., 2005; Jyothibabu et al., 2006; 2015; Ramani et al., 2010; Martin et al., 2008; 2010; 2012). In effect, the numerous land-filled roadways that have been built up in VBL operate as coastal dams, preventing floodwaters from draining freely to the open waters and then to the SEAS. The TB in the southern sector of VBL generated a wide perennial limnohaline/limnetic region upstream. The TB notably decreased the saline nature of the VBL, especially towards the upstream areas, which is evident in the long-term salinity distribution before and after the construction of the TB (Fig. 6; Balchand, 1983). In addition, these barrages facilitated the collapse of natural ventilation and nutrient regulation by tidal flushing in the interior sectors of VBL, which had evolved over a long period (Kannan, 1979; Gopalan et al., 1983; Balchand 1983; Dinesh Kumar, 1997). The large areas of stagnant freshwater sections created by barrages favoured the proliferation of water weeds (Balchand, 1983; Unni and Nair 1995; Dinesh Kumar, 1997), where they took advantage of the eutrophic environment and posed a serious ecological threat (Balchand, 1983; Unni and Nair 1995; Menon et.al., 2000). But on the other hand, in the past, saltwater used to reach the vast areas of the VBL that are now infested with water weeds, making any water weed proliferation difficult. Restricting natural tidal ventilation and flushing enhanced nutrient and pollutant buildup, as well as siltation in the VBL (Balchand, 1983; Unni and Nair 1995; Menon et.al., 2000; WISA, 2013)

The current human-caused flow restrictions in the VBL, which make the region favourable to water weed growth, have been there for a long time, and a historical review of them is provided in Kannan (1979) and Gopalan et al (1983). In the 1930s, the Government Kerala considered mega environmental modification proposals in the Kuttanad of VBL, including (a) fast drainage of floodwater from Kuttanad into the adjacent SEAS during the Monsoon seasons, and (b) prevention of saline water intrusion into the Kuttanad during the Pre-Monsoon (March to May) to intensify paddy cultivation in the Kuttanad. After two decades of planning, these proposals were finally initiated in the 1950s, with (a) a spillway at Thottappally (30 km south of Alappuzha) to drain floodwaters from the Achancoil-Pamba river basin into the SEAS, (b) a saltwater regulator/barrage at Thanneermukkom to prevent saline water intrusion into the Kuttanad and (c) a 42 km land-filled link road between townships Alappuzha and Changanacherry (AC Road), which was built cutting across the VBL in a west (Alappuzha) and South-east-(Changanacherry) direction. The Thottappilly spillway opened in 1955, the Thannermukkom Barrier in 1974, and the AC road in the 1980s. Unfortunately, none of the above engineering structures in the VBL had the desired effect, and they all became typical ‘ecological backlashes' (Kannan, 1979; Balchand 1983; Dinesh Kumar, 1997; Sreejith, 2013) due to the outweighing negative environmental effects they impose on the environment. These include; (a) the Thottappilly spillway, which was built to prevent flooding in the upper Kuttanad, failed miserably and actually made flooding worse in those regions and also supported the proliferation of water weeds due to the stagnancy of the water (b) The Thannermukkom barrier, which prevented saline water intrusion into the paddy fields in the ‘Kayal nilangal' in the lower Kuttanad and ‘Karappadangal' in the upper Kuttanad, caused massive environmental degradation through eutrophication, a decline in fishery stocks, the spread of epidemics and the proliferation of water weeds (Kannan, 1979; Gopalan et al., 1983; Balchand, 1983; Dinesh Kumar, 1997; Sreejith, 2013) and (c) the 42 km long land-filled AC road, which was built for better transportation, failed miserably due to floodwater inundation during the peak SWM, and in recent years, a week of consistent monsoon rain has been enough to flood this road in several kilometres on various sections.

With the awful frequent floods in the region in recent years and restriction of vehicle movement due to the submergence of the land filled AC road at multiple points, the Kerala government has now adopted to construct the ‘elevated highway' at several points along this road. The long, land-filled AC road over the last several decades accumulated human settlements on both sides, increasing the direct discharge of domestic sewage into the neighbouring AC canal, which was before acted as the major waterway connecting the townships of Alappuzha and Changanachery. Currently, the AC canal is the home to large meadows of water weeds, though there is the occasional physical removal of water weeds from certain sections, which is unscientific and inadequate in offering a permanent solution (Supplementary Material 4). Similarly, several other land-filled minor highways intersect the VBL's water bodies (for eg. Ambalappuzha-Thiruvalla road), exacerbating the region's stagnancy and waterlogging concerns, and all of this has aided one way or the other the fragmentation of water bodies, eutrophication and the spread of water weeds in the VBL (Gopalan et al., 1983; Balchand, 1983; Dinesh Kumar, 1997; Revichandran et al., 2012; Sreejith, 2013; Padmakumar et al., 2019). In conclusion, neglect of Kuttanad's hydrological regime is a major contributor to the region's deteriorating environmental regime, and it is clear that in the past, far more attention was paid to socio-political interests than scientific management of the hydrological regime (Kannan, 1979; Gopalan et al., 1983; Balchand, 1983; Dinesh Kumar, 1997, Sreejith, 2013; WISA, 2013).

4.3. Agriculture, reclamation, and tourism

The Kuttanad in the VBL is known for its extensive rice/paddy fields, and its landscape comprises roughly 1100 km^2, of which approximately 304 km^2 is below sea level (MSSRF, 2007; Sreejith, 2013). Most of the land that is now inhabited in the Kuttanad was created by reclaiming waterlogged areas over time (Kannan, 1979, Gopakumar and Takara., 2009; MSSRF, 2007; Vallikappen, 2012; Sarath Chandran and Subrata, 2018). Its landscape consists of Kayalnilangal (8100 ha), Karinilangal (6,075 ha), and Karappadangal (42,505 ha). Kayalnilangal is situated below sea level and even though the soil is acidic here, if the saline intrusion is avoided, the area can be used for paddy cultivation twice a year. Karinilangal is waterlogged, and due to the presence of high acidity, it contributes very little to rice cultivation. Karappadam is the reclaimed land, which constitutes the North Kuttanad, Middle Kuttanad, and Upper Kuttanad with a relatively fertile area that is less affected by saline water intrusion. During the SWM, floodwaters enter Kuttanad from upstream catchments, which carry a substantial sediment load that eventually spreads across the lowland. During high floods, water overflows the bunds, roads and homes, inflicting a chaotic situation in the region. Farming is the main source of income for the people of Kuttanad, and in the lowlands, paddy cultivation predominates, whereas the bunds and reclaimed land are used to plant coconut palms, pepper, bananas, and yams. The reclamation of land for habitation and the expansion of homestead cultivation has reduced the available area for floodwater storage, causing flood levels to rise. Also, the overloading of fertilisers and pesticides eutrophicates and pollutes not only the agricultural fields but the entire VBL due to flushing and seepage. The Indo-Dutch programme n the 1980s estimated a quantity of 25,000 tonnes of fertiliser and 500 t of highly toxic pesticides in the 55,000 ha of Kuttanad paddy fields annually (Prakash Pillai, 2015).

The VBL has a long history of indiscriminate reclamation by different sections of society, which includes farmers, agriculturists, industrialists and tourism promoters, all contributing to its considerable shrinkage and present stagnancy of water bodies conducive for water weeds proliferation. A significant share of the major environmental degradation in the Kuttanad region is the result of the government's weighted strategy to establish a rice-based economy in Kerala without considering the long-term ecological backlashes of significantly altering a very sensitive ecosystem that has evolved over thousands of years. (Gopalan et al. 1983) illustrated the specifics of the large-scale reclamation of VBL for agriculture over several decades, as well as the environmental imbalances that resulted. By offering financial support in the late 1880s, the then-Royal Government of Travancore encouraged farmers to recover the open waters of the VBL to extend their agricultural fields. In that period, land reclamation and flood management in the Kuttanad were largely carried out by private farmers and during this early stages of land use pattern changes, approximately 2,226.27 hectares of the open waters of VBL were reclaimed for agriculture. Following that, reclamation efforts were suspended by a government notification in 1903, based on the assumption that rising siltation induced by reclamation would jeopardise Cochin Harbour's existence.

Large-scale reclamation resumed in 1912, resulting in an additional 5,223.15 ha reclaimed by 1931. Between 1941 and 1950, the subsequent reclamation in VBL resulted in 700 ha of QST-block and 620 ha of R-block (Gopalan et al., 1983).

In addition to the large-scale reclamation for the expanse of agriculture in the Kuttanad, widespread isolated reclamation all along the VBL in the 1900s resulted in an additional area of about 1,500 ha being developed by private owners for agriculture, cottage industry, and housing along the banks of the main channels, connecting canals, and islands (Gopalan et al., 1983). Subsequently, farmers desired to transform the vast reclaimed paddy fields in the Kuttanad region for double or triple cropping of paddy, whereas previously only one crop of paddy could be grown each year. To facilitate this desire of the farmers, the Kerala government built a spillway for flood control at Thottapally in 1955 and a saltwater barrage at Thannermukkom in 1974 to prevent the intrusion of saline water into the Kuttanad region. The tremendous ecological imbalance caused by these major hydrological changes in the VBL completely upsets the natural balance and periodic flushing of the VBL. Interestingly, over time, the subsistence farming practised in Kuttanad before the 1990s had been largely replaced by large-scale commercial harvesters through increased mechanization, which helped them to reduce the labour involved in paddy cultivation, thereby obtaining an increased profit from paddy culture (Kannan, 1999).

The recent boom in tourism activities in the VBL is another factor degrading water quality and encouraging water weed proliferation. The scenic beauty of Kerala's backwaters, particularly of the Kuttanad, is popular the world over, making tourism a booming industry in the region. Tourism is primarily promoted in the region through hundreds of houseboats plying and countless tourist resorts established along the waterfront on the banks of VBL, especially in the Kuttanad region. The Kuttanad houseboat tourism began in the early 1990s, and the industry that began with manually propelled boats (powered by oars) and only one room now offers ineffable luxuries. The industry supports over 8,000 permanent jobs, excluding those associated with houseboat tourism (Michael, 2017). Nearly 1,500 houseboats are cruising Kerala's backwaters, but only 638 have legal operating licences and according to a recent study, the maximum number of houseboats that can cruise on VBL is 328 and any addition to this could endanger the wetland ecosystem (Abdulla et al., 2014).

A sewage treatment plant for houseboats plying in Kuttanad was established only in 2013, and before that, houseboats used to discharge sewage directly into open waters of VBL with no treatment (Michael, 2017). The district tourism promotion council regulates the use of the treatment facility, which is only available to houseboats with a valid licence. Other houseboats continue to pollute the VBL by discarding organic and inorganic trash directly into the water. Every day, the Kerala houseboat tourism industry is expected to dump 4.25 tonnes of garbage into the VBL and inorganic waste accounts for 1.2 tonnes of total waste deposited each day (Michael, 2017). The expansion of backwater tourism has resulted in encroachment on open waters of the VBL (MSSRF, 2007; Roopa and Vijayan, 2017). The VBL is also being encroached upon for the construction of homestays, tourist resorts, and other commercial structures to attract tourists. The encroachments are intended to maximise the waterfront for tourist resorts, which is one of Kuttanad's main ecological concerns in recent times. The invasion of the lake causes the water bodies in the wetland to shrink, exacerbating the problem of solid waste discharge into the water (MSSRF, 2007; Roopa and Vijayan, 2017). In short, while paddy agriculture was primarily responsible for the reclamation of VBL in the Kuttanad region until the 1980s, the present fall in the open waters of VBL is due to the development of tourism and its necessary amenities (MSSRF, 2007; Roopa and Vijayan, 2017). A recent study found that the reclamation of the open waters of the VBL is still a severe problem, as it observed that the water body area of 195.95 km^2 in 1990 declined to 140.84 km^2 by 2014 (Raju and Manasi, 2019), which is a matter of concern to immediately tackle to conserve the ecology of the VBL. Due to human intervention, the already shrunk, fragmented and stagnated water bodies of VBL are so conducive to the rapid proliferation of water weeds.

4.4. Industries, urbanization and human settlements

Several industries, including chemical, petroleum, cement/ores, paper, coir, and distillery/food drinks, line the banks of the VBL (Fig. 1). The VBL's centre and northern sections, as well as the banks of the River Periyar, are semi-urbanized areas dominated by the chemical, petroleum, cement, ores, and paper industries. There is a dense concentration of large industries on the banks of the Periyar River in the Udyogamandal area, 10 kilometres north of Kochi seaport, which is estimated to discharge more than 260 million gallons of untreated wastewater into the Periyar River every day (Priju and Narayana, 2007). Previous research indicates considerable nutrient enrichment as well as increased phytoplankton biomass production in the River Periyar as a result of these industrial activities, rising urbanisation, and human density (Gopalan et al., 1983; Joy et al., 1990). During India's pre-independence time (1940s), factories were primarily developed along river banks with little/no regard for the complexities of VBL hydrodynamics and its possible implications for the sinking and redistribution of chemical and effluent discharges. Due to a lack of technology and prohibitively expensive sewage treatment costs, effluents were finally released straight into the VBL's northern sections (Qasim, 2003; Jyothibabu et al., 2006). Ambalamugal has witnessed many fish kill events in Chitrapuzha since 1973 as a result of the harmful effects of industrial pollutants in waste discharge into open waterways. The coir and beverage industries are also located in the southern sector of the VBL, and their effluents and wastes are directly discharged into the open waters of the VBL, which has various socioeconomic implications (Gopalan et al., 1983; Dinesh Kumar, 1997; Padmakumar et al., 2002, 2019).

Urbanization and rapid human settlements in townships and cities are natural outcomes of improved transportation and living conditions, and the same is true along the banks of the VBL, where there has been a significant increase in human settlements in recent decades (MSSRF, 2007; WISA, 2013 Sreejith, 2013; Raju and Manasi, 2019). Similarly, human settlements have increased significantly along the sides of highways and bunds built, as well as along the banks of the VBL during the past several decades. As a natural outcome, more and more crisscrossing roads have been built, causing further fragmentation and stagnation of the water bodies (MSSRF, 2007; Gopakumar and Takara., 2009). Resulting from all of this, the highly fragile and vulnerable VBL is subjected to environmental stress and increased nutrient loading (Gopalan et al., 1983; Joy et al., 1990). Agricultural runoff and sewage from Alappuzha and other cities also enter the VBL, and it is estimated that the Kochi City alone produces 2,550 million litres of sewage each day, which flows untreated into the VBL. During the summer, the total dissolved solid content of water reaches 53,750 mg/l but drops to 160 mg/l during the wet season. It is observed that Kochi's present sewage treatment plants barely process water from 1% of the population (Nivya and Pieus, 2016). Even though the majority of individuals utilise a septic tank sewage system, a large number of toilets near the VBL cause direct faecal pollution. Faecal coliform levels of up to 2500 MPN/100 ml have been reported. Kochi Corporation uses the Padiyathupalam, Kalvathi, Rameswaram, Pulimuttu, and Thevara canals to discharge municipal waste containing high levels of particulate organic materials into the estuary (WISA, 2013). Phosphates, sulphides, ammonia, fluorides, heavy metals (mercury, chromium, lead, copper, zinc, and pesticides) are all present in dangerously high concentrations in these discharges (DDT, BHC, and so on) (MSSRF, 2007). Livestock farming (cattle, ducks) is a frequent practice in the increasing human settlements, particularly in the Kuttanad region, and the faecal waste discharged into the open waters of the VBL is another direct source of nutrient inputs into the system. Furthermore, as previously stated, the long, land-filled Alappuzha-Changanachery and Thakazhy-Thiruvalla roads have resulted in the accumulation of human settlements on both sides of the road, increasing the direct discharge of domestic sewage into the already fragmented and stagnant water bodies (Padmakumar et al., 2002; MSSRF, 2007; John et al., 2009).

4.5. Topography, siltation and floods

The terrain of Kerala has highland, midland, and coastal zone in an east-west direction and the Western Ghats Mountain ranges are the highland that runs parallel to India's southwest coast. Six rivers that originate from the Western Ghats flow swiftly through the midland, discharging a massive amount of freshwater and sediment into VBL, especially during the SWM. This heavy inflow of freshwater and sediment remains in the bowl-like VBL for some days before being flushed out into the adjacent SEAS. Due to the narrow sea inlets and the microtidal nature of the VBL, flushing is a relatively slow process, and as a result, heavy siltation is a severe problem in the VBL (Qasim, 1974; Gopalan et al., 1983; Balchand, 1983; Dinesh Kumar, 1997; Gopakumar and Takara., 2009; Karnan et al., 2018), the severity of which is evident in the continuous maintenance dredging operations required for the Cochin Port's ship channel, where it is estimated that a quantity of silt of 10×10^6 m^3 is being removed every year (Balachandran et al., 2005; Rasheed, 1997). The total annual sediment yield from all rivers draining into the VBL is estimated to be 32 million tonnes/year, and as a result, the mean depth of the VBL has reduced from 6.7 m to 4.4 m over the last 8 decades (Padmakumar 2002; Gopakumar and Takara., 2009; Ramani et al., 2010). The VBL depth has reduced over time owing to excessive sedimentation, as evidenced by a considerable decline in its water carrying/holding capacity from 2.4 km^3 in 1960 to 0.6 km^3 in 2000. (Padmakumar 2002, 2019; Ramani et al., 2010). Reclamation and flow restriction through barrages and crisscrossing roads have had their share of augmenting siltation in the VBL in recent decades, and a recent study showed that if the siltation continues at its present rate, the VBL will disappear in 50 years, transforming into extensive swamps (Padmakumar 2002, 2019).

Floods are undeniably an effective way of dispersing waterweed into new areas. When floods occur, the tremendous velocity and erosive force of the water flow increases sediment transport rates and causes severe damage to aquatic plants, creating an open conducive niche for ecologically advantageous plants to thrive (Elton 1958; Friedman et al., 1996; Donaldson, 1997). Flood flow will also transport seeds and plant parts to new locations transforming previously weed-free areas into infested zones (Donaldson, 1997). Thus, flooding causes a disturbance in the existing plant community and this, along with excess nutrients brought in by flood water, will favour the extensive growth of noxious water weeds that can withstand these disturbances (Pysek and Prach 1994., Donaldson, 1997). During the flooding season, rivers drain enormous quantities of freshwater into the VBL, flooding the low-lying regions like Kuttanad. This helps water weeds disperse their propagules and seeds to adjoining canals, streams, ponds, and paddy fields, establishing their healthy populations there. In recent decades, floods have been very frequent in the VBL, which submerge large geographical areas in the VBL. The extent of flooding in the VBL is evident in Fig. 7, which shows that the entire landmasses in the VBL got inundated and appeared as a single open waterbody during the flood in 2018. Exotic weeds have the advantage of exploiting these opportunity windows, empty niches, and the ability to fluctuate resources, making them successful invaders under extreme environmental conditions such as a flood (Fleming and Dibble, 2015).

The increase in depressions and cyclones in the seas around India has a remote impact on the rainfall over the catchment regions of VBL, causing severe floods in the region, and there is a general belief that these changes are linked to the region's long-term climate change scenario (Mishra et al. 2018a; Sudheer et al. 2019). Deshpande et al. (2021) observed a rise in the intensity, frequency, and length of cyclonic storms and extremely severe cyclonic storms over the Arabian Sea in recent decades. During the recent period (2001–2019), the frequency of cyclonic storms in the Arabian Sea increased by 52%. More importantly, it was noted that the last few severe floods in Kerala in the years 2018 and 2019 was triggered by a deep depression formed in the northern Bay of Bengal during the late SWM, in combination with high air moisture content and the orographic effect of the Western Ghats Mountains. Vijayakumar et al., (2021) showed that the flood of 2019 in Kerala was the result of a mesoscale cloudburst event, a highly uncommon and never previously documented phenomenon in the Kerala region. The study suggests that if 2019 is a sign of how global warming will continue to influence this region, changes in cloud structure, as well as the frequency and nature of severe rainfall events, might represent a danger to the Western Ghats ecosystems (Vijayakumar et al., 2021). Furthermore, several dams/reservoirs are situated across the Western Ghats, which provide water for agriculture and hydroelectric power generation (Ramasamy et al., 2019) and it is interesting to see how their opening during the extreme rainfall events aggravates the flood situation in the VBL (Mishra et al., 2018a; Sudheer et al., 2019). For example, the flood of 2018 was caused by two periods of heavy rain in two weeks; the first of these two caused flooding along the banks of certain rivers, and water was released from just a few dams since the rain fell mostly over their catchment regions. Following the initial round of heavy rain, most of the reservoirs in the state were nearing capacity, and most of the land in the region had become water-saturated. As a result, when the second event began a few days later, officials were forced to open the shutters of virtually all of Kerala's main dams. The combination of this intense rainfall and the opening of the dam shutters caused catastrophic flooding in Kerala (Mishra et al., 2018b; CWC, 2018). The latest catastrophic event in this series has just happened in mid-October 2021, which was the result of two depressions forming simultaneously in the Arabian Sea and the Bay of Bengal, causing torrential rainfall and flooding in VBL (Fig. 7**)**. Given the alarming future climate change scenario and the rapidly diminishing water holding capacity of the VBL owing to enhanced siltation (Gopalan et al., 1983; Dinesh Kumar, 1997; Gopakumar and Takara., 2009; Padmakumar 2002, 2019), we anticipate many more severe and frequent floods in the future, which may favour the further dispersal of water weeds and even a change in their current pattern of infestation.

5. Consequences Of Water Weed Proliferation In Vbl

5.1. Ecology and productivity

The spread of water weeds over the last several decades is a problem in many parts of the world (Supplementary Material 5) and it is observed that the introduction of noxious water weeds has many detrimental effects on the aquatic systems, which are summarised in Fig. 8 (Lancar and Krake, 2002; Greenfield et al., 2007; Jayan and Sathyanathan, 2012). It is more worrisome concerning the VBL as the livelihoods of thousands of people are directly or indirectly linked to its extensive networks of rivers, lakes, and canals. Noxious weeds can form a vast canopy over the water surface, blocking sunlight from entering the water column, which affects primary production and results in the collapse of the natural food web existing in such ecosystems (Penfound and Earle, 1948; Holm et al., 1969; Fleming and Dibble 2015). The reduction in photosynthesis harms dissolved oxygen levels, and thick mats of floating weeds further prevent water column mixing because atmospheric oxygen dissolving into surface layers cannot reach deep layers (Lancar and Krake, 2002; Greenfield et al., 2007; Jayan and Sathyanathan, 2012). Extensive growth of plants results in a high amount of organic material in the water column that uses the available oxygen for decomposition, further depleting dissolved oxygen concentrations and affecting the fishes and other fauna, thus reducing total production (Madsen et al., 1991; Madsen, 2004). Floating and submerged water weeds can compete for nutrients with phytoplankton and other native aquatic plants (Van Donk et al., 1993; Weisner et al., 1994; Van Donk and Bund., 2002). It is worth noting that water weeds such as *Eichhornia* can absorb and store large amounts of nitrate and phosphate, lowering their concentration in infested areas of the water body (Rommens et al., 2003). Another ecological aspect of water weed proliferation is increased water loss to the atmosphere in water weed infested areas due to high evapotranspiration rates, which could adversely affect the water conservation strategies (Fig. 8; Arunpandi et al., 2021). Invasive water weeds are often generalist species that can thrive in a wide variety of environmental conditions and can make use of a variety of different resources when compared to native flora (Fleming and Dibble, 2014). Some invading macrophytes can produce allelopathic chemicals that restrict the growth of phytoplankton and affect the fish population and other faunal assemblages. Each year, a huge amount of organic material from extensive mats of aquatic macrophytes sinks to the bottom where it undergoes decomposition (Gopalan and Nair, 1975). These sinking plant parts carry petroleum oil film present in the surface waters of the backwater system (mainly discharged from Cochin harbour where a huge amount of crude petroleum is handled every year) to the bottom layers, creating a toxic environment for the benthic community (Gopalan et al., 1983).

5.2. Faster succession of VBL

Natural freshwater reservoirs age and die in a predictable pattern of succession, as many of the currently existing freshwater marshes and bogs are former lakes and ponds that have undergone succession (Odum, 1983; Horne and Goldman, 1994). Lake succession is mainly driven by the input of organic matter and sediment and as the lake fills up, it loses water and becomes a swamp. The explosive growth of water weeds alters the physical properties of lakes and ponds by fastening eutrophication and ecological succession (Thomas 1977; Abbasi and Nipaney 1986). Invasive species often evolved characteristics of pioneer species which enables them to utilize empty niches or create new niches in the local ecosystem (Elton 1958; Owens et.al., 2008; Khanna et al., 2012; Fleming and Dibble 2014). Thick mats of floating weeds gradually accumulate suspended particles and silt carried into the reservoir by surface water runoff and river discharges, making them efficient substrates for secondary plant communities to grow (Thomas 1977, 1979). Salvinia can form mats of thickness 1–3 meters within only a matter of 3–5 years, gradually forming floating islands (Thomas, 1981). These floating islands together with eutrophicated water columns set the stage for an ecological succession event by supporting the growth of deep-rooted secondary inhabitants and further accumulating silt and mud, drastically changing the shoreline pattern of the water body (Thomas, 1981, 1984). The floating mats of *Eichhornia* and *Salvinia* gradually settle above the littoral zone, touching the banks of the lake. This will help highly competitive invaders like Ipomea and other riparian plants of more terrestrial characteristics grow over the floating islands, establishing a secondary plant community (Fig. 9; Thomas 1977, 1979; Aloo et al., 2013). *Monochoria* is a successful secondary plant on a floating island formed by Eichhornia and Salvinia. The gradual succession of plant communities close to the banks progresses in such a way that it strengthens the floating mats more and more and makes them permanent formations. This will facilitate the growth of rooted macrophytes and semi-aquatic weeds provided that the floating islands can act as substrata, mimicking marshy land over the water column, eventually accelerating the succession. Water weed activity combined with anthropogenic reclamation may result in significantly faster VBL shrinkage than would be predicted over a natural course (Thomas, 1977; 1979; Aloo et al., 2013).

5.3. Socioeconomic impacts

5.3.1. Fishery, navigation and paddy culture

Ecological imbalances caused by water weeds have a profound socioeconomic impact on the large fraction of the residents of Kerala who either directly or indirectly depend on the VBL for their livelihood (MSSRF, 2007; Sreejith, 2013; Raju and Manasi, 2019). Water weed growth harms primary production underwater, which has a reflection in all trophic levels in the food chain, the highest impact being on the fishery. Reduction in biological production impairs the daily income of residents, which brings related social problems like the lower quality of life, malnutrition, susceptibility to diseases, and poor access to better healthcare systems, which in essence makes the affected population vulnerable and reduces their social security (Christiansen and Hunt, 2000; Schultz, and Dibble, 2012; Villamagna and Murphy, 2010). The extensive growth of *Eichhornia* makes it impossible to operate fishing gears and vessels. Bivalve (black clam) is one of the most important bioresources of VBL which has been exploited for many decades (Laxmilatha and Appukuttan 2002; Arunpandi et al., 2021b). Water weed growth alters the phytoplankton production and physical characteristics of the water column making it less favourable for the growth and development of bivalve larvae. Also, the water weeds make it difficult for bivalve collectors to dive down and collect them (Laxmilatha and Appukuttan 2002). Another devastating effect of water weeds is on the Chinese dipnets, which is a major fishing gear used in the VBL and the water weeds mats make its operation impossible. Because Chinese nets are fixed nets with significant financial investments, the complete blockage of many interior channels by water weeds effectively ends their operation for an extended period, posing a serious social issue for those who actively participate in such fishing activities (Supplementary Material 6). Even the Chinese nets on the banks of the Kochi inlets, which are located far from the parent stock of the Eicchorina in the upstream of VBL, are in chaos when a heavy load of water weed biomass is flushed out almost regularly, especially during the Southwest Monsoon season, and settles over their fishing area, blocking and tearing their fishing nets and creating an unpleasant working environment (Supplementary Material 7). Extensive mats of water weeds, particularly *Eichhornia*, pose a significant threat to aquaculture practises because they block and clog the nets and cages in which fish are grown, increase sedimentation on the cages, lowering water quality and dissolved oxygen levels, and cover the surface, preventing fish from feeding, particularly surface feeders (Fig. 8; Supplementary Material 8), which results in lower production and economic loss for the farmers (Abbasi and Nipaney 1986; Mehra et al., 1999; Rommenes et al., 2003). Similarly, huge floating waterweed biomass causes many difficulties for local fishermen, including damage to their fishing gear, and there are even instances of fishermen getting trapped in extensive weed mats and having the fire force service come to rescue them (Supplementary Material 9).

Water weeds have been seen all around the world to have the ability to choke pipes and generators in power plants, hence obstructing navigation (John et al., 2009; Shanab et al. 2010). For many years, the VBL's inherent network of canals, streams, and rivers has been used for transportation, the transfer of goods and agricultural products, and even the collection of drinking water from distant sources (WISA, 2013). Now infested by waterweeds, especially the interior waterways and canals, most of the parts of these canals are not good for navigation and many of them are abandoned. Mat forming weeds restricts the movement of small rowing boats and clog the propeller of large passenger boats and submerged weeds damage the propeller. This in recent years adversely affected the houseboat operation in the interior canals which in turn adversely affect the livelihood of thousands of people engaged in this industry. Many canals abandoned for navigation are very common now in and around Alappuzha Town in the Kuttanad region and also the 32 km AC canal along the sides of the landfilled AC Road linking Alappuzha with Changanacherry, which is not navigable during most of the year due to thick and extensive waterweed proliferations (Supplementary Material 10). Many interior canals located even very close to the Kochi inlet in the central and northern sectors of the VBL also get fully blocked by water weeds and are not navigable almost eight months in a year, except during the Pre-Monsoon (March-May) (Supplementary Material 1 & 11).

The water weeds compete with paddy for nutrition and secrete allelopathic chemicals that affect the growth and productivity of paddy (Schultz and Dibble, 2012; Flemming and Dibble 2015). This increased competition from weeds adversely affect paddy crops in the initial stage of growth and results in a loss of 30 to 60% in total production (Thomas, 2002; Jain, 1975; WISA, 2013). Water weeds' strong survival characteristics make weeding exceedingly difficult, and farmers are compelled to do multiple weedings, which costs a lot of money, and even then, they fail to completely eradicate them (Sands et al, 1983). More than 40,000 ha rice cultivable fields in VBL are under severe threat of infestation by water weeds (Unni, 1973; Jain, 1975). So long-term reclamation to promote agriculture, which has worsened the stagnancy of the VBL and favoured the spread of water weeds in recent decades, is now reversing and affecting paddy production in the region, which can be a natural feedback effect, and as a result, expenses to eradicate weeds from paddy fields would raise paddy cultivation costs.

5.3.2. Epidemic diseases

Water weed mats have the potential to increase the prevalence of vector-borne diseases worldwide (Masifwa et al., 2001; Aloo et al., 2013; Stone et al., 2018). Water bodies infested with Eichhornia and Salvinia have been shown to support the prolific growth of mosquitoes by functioning as their breeding grounds, raising the danger of epidemics of mosquito-borne illnesses such as filariasis, malaria, and dengue. Water weeds make it easier for mosquitos to lay eggs, and their submerged roots provide a safe refuge for mosquito larvae from predatory insects and fish, as well as protection from being transported away by water currents (Chandra et al., 2006; Minakawa et al., 2008; Varshney and babu, 2008). Furthermore, research from around the world has demonstrated clearly that floods and other climate factors may dramatically increase the spread of communicable and infectious diseases (Sachs and Malaney, 2002; Brown and Murray, 2013; Gao et al, 2016; Okaka et al, 2018, Ding et al, 2019). Floods, for example, hasten the spread of water-borne illnesses such as typhoid, fever, cholera, leptospirosis, and hepatitis viral influenza, as well as vector-borne diseases such as malaria, dengue, yellow fever, and West Nile Fever (WHO, 2014). In 2017, infectious illness outbreaks in Kerala were primarily recorded in the Lower Kuttanad area of the VBL, which is most vulnerable to monsoon floods. During the 2017 monsoon, the lower Kuttanad accounted for 70% of all water-borne illnesses recorded in the Alappuzha district (Raju and Manasi, 2019; Rajendran et al, 2021). Aside from the above seasonality, occupational trends in the spread of water-borne illnesses are also visible in the Kuttanad region, and the majority of leptospirosis cases recorded in Kuttanad are from paddy workers, canal desilting labourers, and volunteers who are more exposed to polluted water and soil (Jobin and Prakash, 2020; Rajendran et al, 2021). Currently, the stagnant sewage, particularly in the Kuttanad area, covered with dense water weed growth, provides conducive breeding habitat for mosquitoes (Kannan, 1979). Each year between June and September, when the monsoon rains hit the region, these infectious illnesses reach epidemic proportions (Elamon, 1997; Govindaraj et al, 2018). The region has served as a breeding ground for pathogens and parasites that spread infectious illnesses such as Japanese encephalitis, leptospirosis, dengue fever, and cholera. Concerns about these diseases in Kuttanad arose in the mid-1990s when Japanese encephalitis struck in the form of an epidemic (Kalaiyarasu et al., 2016). In addition to Japanese encephalitis, the Kuttanad region has had outbreaks of malaria, leptospirosis, dengue, chikungunya, and what is generically known as "viral fever" since the mid-1990s (Raju and Manasi, 2019; Shankar et al., 2021; Varughese et al., 2021).

6. Management Of Water Weeds And Challenges

6.1. Mechanical methods

Different methods are practised worldwide for the mechanical removal of water weeds, from traditional handpicking to specially designed modern machinery (Jain, 1975; Jayan and Sathyanathan, 2012). The common mechanical methods used to remove water weed biomass include dredging, drying, mowing, hand cleaning, chaining, burning, and cutting (Jain, 1975; Madsen, 1997; Lancar and Krake, 2002; Greenfield et al., 2007; Jayan and Sathyanathan, 2012). The basic traditional approach, practised in the Kuttanad paddy fields, consists of emptying the paddy fields, collecting weeds into piles, and then hauling them to the boundary bunds with coconut leaves (Jayan and Sathyanathan, 2012). Free-floating weeds in canals and other bodies of water are either shredded into pieces and left to decay in the water column itself, or harvested and dumped on the shore where they undergo death and decay. Large-scale mechanical removal seems to have instant relief, but the results are temporary and come with many ecological and economic backlashes (Lancar and Krake, 2002; Greenfield et al., 2007; Jayan and Sathyanathan, 2012). Most weeds are capable of a vegetative mode of propagation and shredding helps their accelerated growth. Weeds like *Eichhornia* exhibit both a sexual and an asexual mode of propagation and produce dormant seeds, which makes it nearly impossible to remove them completely by mechanical means. In Kerala, each year a huge amount of money is spent to eradicate water weeds blocking canals and streams, but their reinfestation happens quickly, making such practices economically not feasible. Also, the sudden removal of bulk quantities of weeds may have associated ecological consequences (Jain, 1975; Lancar and Krake, 2002; Greenfield et al., 2007 Jayan and Sathyanathan, 2012). Shredded plant parts sink to the bottom where they undergo decay, depleting the dissolved oxygen level. It also increases the nutrient load by organic decomposition and lack of absorption of nutrients, which the weeds would otherwise do. Also, the mechanical disturbance created by the weed cutters in the water column and the bottom sediments causes the presence of very poor water quality due to increased turbidity. These sudden shifts in nutrient and physical characteristics of the water column have an impact on plankton and nekton, often resulting in algal blooms (Bryant 1970; Lancar and Krake, 2002; Greenfield et al., 2007, Jayan and Sathyanathan, 2012; Magas-Ramirez and Gutierrez, 2004). Many water weeds also collect heavy metals from the surrounding water inside their bodies, and when they are harvested and heaped on the shore, especially near human settlements, there is a risk of heavy metals leaching out from decaying plants and spreading to neighbouring regions or possibly polluting drinking water resources. However, the mechanical approach is still commonly used in many regions of the VBL, notably in stagnant canals near to human settlements, which become blocked each year, making navigation and other public amenities in these water bodies difficult (Supplementary Materials 10 & 11).

6.2. Chemical and biological methods

Chemical control of water weeds is often easier, faster, and less expensive than mechanical approaches. Many herbicides such as 2, 4-D, glyphosate, and MSM are used in India for water weeds and a list of their target plant species is given in Table 1. However, there is always a worry that the chemical residues from the herbicide can remain in the body of water, posing a threat to aquatic animals and making the water unsuitable for irrigation purposes, which has limitations in large ponds and lakes where there is little or no control over water usage (Lancar and Krake, 2002; Jayan and Sathyanathan, 2012). Although certain weeds can be chemically controlled for months or even years, weed recurrence is frequent. The extent of the weed issue, the cost of additional herbicide application, and the possibility for cumulative residue levels should all be considered when re-treating. Herbicide misuse, whether intentional or accidental and worker safety are common problems. Misuse can harm the environment. Even correct pesticide application can cause nutrients from decomposing vegetation to enter the water, causing transient algal blooms, low oxygen levels, and fish kills, especially in the summer (Lancar and Krake, 2002; Jayan and Sathyanathan, 2012). Increasing chemical residues in treated waterways and organic matter sedimentation are two more issues. Many herbicides and algaecides need many hours or days of waiting before using water for drinking, irrigation, pleasure, or fishing (Lancar and Krake, 2002; Jayan and Sathyanathan, 2012). There is no published information on the use of herbicides to manage water weeds in the VBL, and given the numerous interconnected canals and network of water bodies associated with the VBL, extreme caution and a thorough environmental impact study are required before using herbicides to control water weeds here.

Table 1
Some useful herbicide chemicals used in acquatic weed control

(adapted from Jayan and Sathyanathan, 2012)

S. No.	Herbicide/ weed-killer	Type of acquatic weeds controlled	Dosage	
			From	**To**
1	Copper Sulphate	Algae and submerged weeds	0.5 mg L^{-1}	2 mg L^{-1}
2	Dalapon	Emergent weeds	1% solution + 0.1% surfactant	2% solution + 0.1% surfactant
3	Dichlobenil	Emergent floating and submerged weeds	1 mg L^{-1}	2 mg L^{-1}
4	Diquat	Floating and submerged weeds	0.50 mg L^{-1}	
		Emerged and floating weeds	1.0 Kg ha^{-1}	
5	Diuron	Submerged floating and emergent weeds	0.5 mg L^{-1}	1.5 mg L^{-1}
6	Endothall	Submerged weeds	0.5 mg L^{-1}	2.5 mg L^{-1}
7	Fenac	Submergd weeds		
8	Fluridone	Submerged and floating weeds	0.1 mg L^{-1}	1.0 mg L^{-1}
9	Glyphosate	Emergent and floating weeds	1.8 kg ha^{-1}	2.1 kg ha^{-1}
10	Hydrogen peroxide	Submerged weeds	10 mg L^{-1}	20 mg L^{-1}
11	Paraquat	Emerged and floating weeds		
12	Simazine	Floating weeds	0.5 ppm	1 ppm
13	Sodium arsenite	Submerged weeds	5 mL L^{-1}	8 mL L^{-1}
14	Triazines	Floating and submerged weeds	0.05 mg L^{-1}	1 mg L^{-1}
15	2, 4D	Submerged and floating weeds	2 Kg ha^{-1}	10 Kg ha^{-1}
		Submerged weeds	1 mg L^{-1}	
	2,4-D Ester	Emergent weeds, floating weeds, submerged weeds.	0.5 Kg/ha	1 Kg ha^{-1}
	2,4-D Amine	Emergent weeds, floating weeds	0.5 Kg/ha	1 Kg ha^{-1}

S. No.	Herbicide/ weed-killer	Type of acquatic weeds controlled	Dosage	
			From	To
	2,4-D Sodium	Emergent weeds, floating weeds	0.5 Kg/ha	1 Kg ha^{-1}

Biological control entails introducing a natural enemy (grazer) to the weeds in their infested region. It is seen as the most ecologically friendly method of managing invasive weeds through top-down control in the food chain, as the absence of efficient grazers in the ecosystem is one of the key reasons for water weed proliferation (Lancar and Krake, 2002; Jayan and Sathyanathan, 2012). Numerous insects have shown promising results in removing the research area's two most prominent aquatic weeds, *Salvinia* and *Eichhornia* (Lancar and Krake, 2002; Jayan and Sathyanathan, 2012). Cyrtobagous Salviniae, a coleopteran weevil, was found to successfully control *Salvinia* in Australia, Papua New Guinea, Namibia, and South Africa (Room et al., 1981; Forno and Bourne, 1985; Room and Thomas, 1985; Lancar and Krake, 2002; Coetzee et al., 2007a,b; Jayan and Sathyanathan, 2012). In the 1980s, *Cyrtobagous salviniae* were attempted in the Kuttanad region by Kerala Agricultural University (Jayan and Sathyanathan, 2012). Based on the success of *Cyrtobagous salviniae* in test sites in different parts of Kerala, weevil-infested weed mats were dispersed across Kuttanad for the biological management of Salvinia proliferation. It is reported that within three years following the introduction and establishment of *C. salviniae* in Kuttanad, most of the canals that had been abandoned due to the weed problem were navigable again (Jayan and Sathyanathan, 2012), but its efficacy on a long term basis is uncertain considering the present level of *Salvinia* infestation in many sections of the VBL.

To manage *Eichhornia*, many exotic insects, including *Neochetina eichhorniae*, *N. bruchi*, and *Orthogalumna terebrantis*, were dispersed in various sectors of the VBL. *O. terebrantis*, which was released in the 1990s, established itself all over the release locations and spread far and wide throughout the Kuttanad. It was observed that in VBL, where *N. eichhorniae* and *N. bruchi* were slow to control *Eichhornia* compared to *O. terebrantis*, which provided better results in some regions. *Cornops aquaticum*, a semi-aquatic grasshopper endemic to South Africa, is one of the most difficult natural enemies of *Eichhornia* (Perkins 1974). *C. aquaticum* has been demonstrated to reduce the density of dense *Eichhornia* mats even in eutrophic situations and to cause plant death in nutrient-deficient circumstances (Bownes et al., 2010a). It was also observed that the combined activity of *C.aquaticum* and *N.Eichhorniae* is more successful in destroying *Eichhornia* than any other biocontrol method (Bownes et al., 2010b). Similarly, the weevil *Neohydronomus affinis* is found to be effective in controlling *Pistia*, but due to their slow growth, it may take several seasons to achieve optimum effects (DeLoach et al., 1976; Harley et al., 1990; Coetzee et al., 2007a,b). Table 2 includes a list of potential biocontrol agents for the water weeds in VBL.

Table 2
Organisms used for biological control of aquatic weeds

(adapted from Jayan and Sathyanathan, 2012)

S. No.	Name of the aquatic weed	Biocontrol agents
		Anthropods
1	*Alternanthera philoxeroides*	*Agasicles hygrophila*
2	*Eichhornia crassipes*	*Neochetina eichhorniae and N. bruchi Orthogalumna terebrantis* *Sameodes albiguttalis*
3	*Hydrilla verticillata*	*Parapoynx diminutalis* *Bagous spp.* *Hydrllia spp.*
4	*Pistia stratiotes*	*Neohydronomous pulchellus Epipsamonia*
		pectinicornis
5	*Salvinia molesta*	*Cyrtobagous salviniae and C. singularis* *Paulinia acuminata*
		Fungi
6	*Alternanthera phioxeroides*	*Alternanthera alternantherae*
7	*Eichhornia crassipes*	*Alternaria alternata* *A. eichhorniae* *Cercospora rodmanii* *Fusarium eguisetii*
8	*Hydrilla verticillata*	*Fusarium roseum culmorum*
9	*Pista stratiotes*	*Cercospora sp.* *Scierotium rolfsi*
10	*Salvinia molesta*	*Myrothecium roridum*
		Herbivorous fish

S. No.	Name of the aquatic weed	Biocontrol agents
11	Aquatic weeds	*Ctenopharyngodon idella* *Hypophthalmichthys molitrix* *Tilapia melanopleurea* *Osphronemus goramy*

Even with many biological control methods attempted in the past, water weed infestation has drastically expanded in the VBL in recent decades, indicating the insufficiency of the strategies adopted (Jayan and Sathyanathan, 2012). The reality is that, while biological management of water weeds has shown encouraging results, particularly at the experimental level, it necessitates routine monitoring and post-release evaluation of natural enemies in the new habitat (Balchand, 1983; Jayan and Sathyanathan, 2012; Simpson et al., 2020; Datta et al., 2021). Several limiting constraints, like complex hydrodynamics and frequent flood situations, are likely limiting the efficacy of the biological management of aquatic weeds in the VBL. It is important to note that the biological control agents in many parts of the VBL can be washed away by tidal flushing and flood water in the VBL, and therefore, maintaining a sufficient population of the biocontrol agents in the waterweed infested region is a real challenge in such situations. Furthermore, most biological controls appear to have less effect in eutrophicated environments because the weed population can employ increased nutrient load to counteract the damage caused by insects and herbivores, swiftly recovering their standing population (Coetzee et al., 2007b; Bownes et al., 2010a). In this context, an integrated strategy may be used to address this obstacle, and it was observed elsewhere that sublethal quantities of glyphosate, a less toxic herbicide to the local environment, combined with biological agents, produced the best results in eliminating *Eichhornia* (Jadhav et al., 2008). But surely more detailed feasibility and environmental impact studies on all these aspects need to be conducted based on the varying hydrographical and socio-economic settings prevailing in the different sections of the VBL.

7. Future Of The Water Weed Control

7.1. Current spread and new invasions

Looking into the current status of the water weed proliferation in VBL, it is important to take comprehensive approaches (control and preventive measures) to curb the spread of already existing weeds and to stop the further introduction of any new weeds (Jayan and Sathyanathan, 2012). The lack of proper legislation to prevent the import of exotic plants needs to be considered urgently to create a legal framework to prevent the introduction of exotic plants in the future, even without any clue as to how such actions affect the native environment. At present, several methods, including physical, chemical, and biological methods, are employed to control aquatic weeds. But none of them is efficient at eradicating water weeds. Hence, there is a great scope for novel technologies that can effectively remove weeds without causing damage to the ecosystem. Due to their long-term impacts on the water column, herbicides are not extensively used to control aquatic weeds, especially in open waters. The development of herbicides that do not harm the environment in the long term is a requirement for the future, considering the rapidity of the water weeds' spreading. But then herbicide resistance in water weeds could be a concern in the future. It was noted that water weeds such as *Hydrilla* have gained resistance to fluridone in some parts of the world (Michel et al., 2004). It was also found that sexually reproducing weeds like *Eichhornia*, which is the most dominant waterweed in VBL, are more likely to develop herbicide resistance (Varshney and babu, 2008).

Undeniably, long-term weed control must be comprehensive, depending on the site's specific needs, and the integration of environmental data, weed biology, ecology, and technology is essential for successful and safe management (Jayanth and Visalakshy, 1989; Shelton and Murphy, 1989; Jayan and Sathyanathan, 2012). Such integrated weed management should include cultural, mechanical, and biological weed control, which essentially requires research, long-term planning, and implementation with the active involvement of the residents along the VBL. Jayan and Sathyanathan (2012) showed that the recommendations of the MSSRF (2007) suggested the total elimination of water weeds from Kuttanad through a systematic programme and concerted follow up over many years, which would physically remove the weeds and cleanse the waterways, allocating around $ 6 million in Indian rupees. It’s a reality that even with all these initiatives in the VBL, the waterweed infestation is increasing alarmingly, which has been reported regularly in print media in recent times (Supplementary Materials 1,2, 10,11, 12).

World over, management of water weeds though their human utilisation is considered to be a great eco-friendly idea for limiting their geographical spread (Ghosh, 2010; Nagendra Prabhu and Suresh Chandra, 2012, Anoop et al., 2014, Nagendra Prabhu, 2016). Researchers revealed numerous applications for water weeds, particularly *Eichhornia*, the details of which are presented in Table 3. Though there are many options available, currently they have many limitations; some have limited scope, while others have impediments to their cost-effectiveness and also for adopting as a long-term technique. The creation of value-added goods from weeds will allow people who live near water bodies to create revenue, which could improve their economic situation while reducing the weed spread (Suresh Chandra et al., 2005; Jayan and Sathyanathan, 2012; Anoop et al., 2014; Nagendra Prabhu, 2016). *Eichhornia*, has high-quality plant protein, making it an excellent choice for animal feed (Indulekha et al., 2019; Ilo et al., 2020). The cellulose content of the water weeds can be used in microbial media and bioreactors (Kivaisi and Mtila, 1997; Priya and Selvan, 2017; Arana-Cuenca et al., 2019; Bronzato et al., 2019). Its flower pigments are also extracted (Priya and Selvan, 2017; Gopika et al., 2018). *Eichhornia* pulp has the potential for use in handicrafts, biodegradable disposable plates and glasses, mushroom growing substrate, paper, and a variety of other items (Suresh Chandra et al., 2005, Nagendra Prabhu and Suresh Chandra, 2012, Anoop et al., 2014, Nagendra Prabhu, 2016). Although many of the above possibilities are explored at the laboratory level, before expanding these possibilities to a broad scale, additional research on their scope, ecological and economic viability, and their potential for application in the current ecological and social situation in the VBL is required. Water weeds such as *Monochhoria* and *Limnocharis* are used as human food in some parts of the world (Nishan and George, 2018b; Athira et al., 2019), but this possibility must be considered very carefully in the case of VBL because these weeds have the potential to concentrate heavy metals (Ingole et al., 2003; Nishan and George, 2018b; Arunpandi et al., 2021) and their high concentrations in heavily polluted environments may harm human life when consumed.

Table 3

Some potential application of the water weeds.

SL.No.	Potential uses	Salient observations	References
1	Removing pollutants	Removal of excess nutrients from water bodies using extensive beds of *Salvinia molesta*	Harley and Mitchel 1981
		Pistia stratiotes acts as a hyper accumulator, removing organic compounds, trace metals and radio nuclides from the polluted water bodies	Sinha et al., 2006
		Efficient exclusion of heavy metals such as Arsenic, chromium, mercury, nickel, lead, zinc from water bodies using aquatic weeds.	Ingole et al., 2003; Arunpandi et al., 2021
2	Phytomedicine	*Hydrilla verticellata*, a low-fat protein containing nutrients, vitamin b-12, iron, Mg, hundreds of enzymes and chlorophyll. Used for anti-septic and healing remedy.	Timon, 1996; Pileggi, 2004
		Anti-bacterial and anti-tumour activity of *Hydrilla verticillata* and its use in improving digestion and gastrointestinal function, blood circulation, neurobiological health and cardiovascular function	Araki et al., 2003; Pal et al., 2004; Pal et al., 2005.
		Limnocharis flava as a cure for rheumatism	Haynes and Les, 2004
		Antioxidant and anti-inflammatory potential of leaves and root extract of *Monochoria vaginalis*	Chandran et al., 2012
		Monochoria vaginalis as a potential antioxidant and anti-cancerous agent	Prabha and Nivethitha, 2019
3		*Limnocharis flava* as a fodder in piggery	Waterhouse, 2003
	Animal feed/ biogas	Using *Salvinia molesta* in composting, biogas production, animal feed and removal of nutrients from polluted water bodies	Vandecastede et al.,2005
		Biogas production using plant biomass	Jayaweera, et al., 2007
		Extracting nutrients from *Monochoria vaginalis* as a food supplement.	Chandran and Parimelazhakan, 2012
		Pisia stratiotes as a substrate for biogas production and exploiting the biomass for biofuels through GM bacteria	Julias et al., 2012
		The potential bioenergy recovery from anaerobic digestion of *Eichhornia* and its co-digestion with fruit and vegetable waste.	Mathew et al., 2015

SL.No.	Potential uses	Salient observations	References
		Limnocharis flava as a nutrient rich feed for domestic livestock	Chandran and Ramasamy, 2015
		Eichhornia as a potential fodder plant for grass carp (: Leaf meal was more appropriate than whole plant.	Mahmood et al., 2018
4	Enzymes	Production of commercially important Cellulase enzyme from *Eichhornia*	Suresh Chandra et al., 2005; Kurup et al., 2005
		Bacterial cellulase production from *Eichhornia*	Nagendra Prabhu and Suresh Chandra, 2012
5	Phytoremediation	*Hydrilla verticillata* shown to be a hyper accumulator of Hg, Cd, Cr and Pb.	McCutcheen et al., 2004
		Using aquatic weeds for phytoremediation of nitrogen	Fox et al., 2008; Nahar, 2012; Zhang et al., 2018
		Removal of aquatic macrophytes from water bodies helps efficient removal of excess nutrients.	Akinbile and Yusoff, 2012
		Eichhornia as a viable phytoremediation agent to reduce the pollution caused by slaughterhouse effluents.	Canazart et al., 2017
		Using *Salvinia molesta* as an eco-friendly phytoremediation agent for dye removal.	Al-baldawi et al.,2020
6	Households/ Compost	Production of organic manure as substratum for mushroom cultivation	Anoop et al., 2014
		Making value added products such as biomass briquettes, biodegradable nursery pots, toys, disposable plates and other household utensils, handicraft and composting manure for mushroom culture.	Nagendra Prabhu, G, 2016
		Utilization of *Eichhornia* as compost in agriculture, with special reference to turmeric.	Indulekha and Thomas, 2018
7	Phytochemistry	Leaves of *Pistia stratiotes* contains high protein, stigmatane, essential amino acids and minerals.	Ghani, 2003
		Separating beta-carotene enriched extraction from *Eichhornia*	Panchanadikar et al., 2005

SL.No.	Potential uses	Salient observations	References
		Converting cellulose from *Eichhornia* into hydrogel which shows augmented water absorption capacity with glutaraldehyde as an additive.	Lalitha et al., 2012
		Bioethanol production from *Eichhornia* by microbial and dilute acid pre-treatment without any additional cellulose.	Rezania et al., 2016
		Manufacturing chemicals from *Eichhornia* using $FeCl_3$ as low-cost and nontoxic oxidant	Liu et al., 2018
		Extraction of natural and eco-friendly dye from the flowers of *Eichhornia*	Gopika et al., 2018; Sreekuttan et al., 2018; Priyanka, 2021
8	Antimicrobial activity	*Pistia stratiotes* as a rich source of bioactive compounds, showing antibacterial, antiviral and anti-algal activities.	Sridevi et al.,2010; Sohail et al., 2011; Yi et al., 2012
9	Furan	The high potential of furfural production from *Eichhornia*	Poomsawat et al., 2019
10	Biosorbent	*Eichhornia* petiole as an efficient adsorbent of toxic Congo red dye.	Rahman et al., 2019

7.2. Climate change on water weeds

Long-term climate change may have an impact on water weed proliferation in three ways. The concentration of CO_2 in the atmosphere has increased significantly during the last century as a result of anthropogenic activity (Nanaki and Xydis, 2018; Vale et al., 2020; Moodlay, 2021). CO_2, a greenhouse gas, is presently warming the atmosphere, causing global climate patterns to alter. Temperature and CO_2 concentration have a direct impact on plant life. It has been shown that high CO_2 concentrations boost biomass and flower production in some terrestrial weeds, such as *Parthenium*, making them adaptive to survive in such conditions and an effective competitor to native plants. Climate change can affect or disrupt the distribution pattern of current water weeds, or it might create favourable circumstances for the invasion of new exotic weeds (Dukes and Mooney, 1999; Hellmann et al., 2008; Randall, 2007; Clements, and Jones, 2021). However, there is no solid scientific understanding of how long-term increases in CO_2 and temperature affect the dominant waterweeds in the VBL, so there is a need for scientific research on these aspects, which would be very useful in planning future water weed management and designing mitigation and adaptation measures. Weed responses to various control methods may also change as a result of changing climatic circumstances, particularly biological control strategies because climate change has a direct influence on organisms utilised as biological control agents (Hellmann et al. 2008). Increasing depressions and cyclones, as well as the related torrential rains and more frequent floods, have occurred in the VBL in recent decades as a result of the region's long-term climate change scenario, which is a particularly concerning element for future water weed control in the region. Given the alarming future climate change scenario and the rapidly diminishing water holding capacity of the VBL due to heavy siltation, many more severe and frequent floods in the future could be expected in VBL, which may favour further dispersal of water weeds and even a shift in their current pattern of infestation.

8. Water Weeds Management In Vbl

Aquatic plants, particularly water weeds, eventually become overabundant or unwanted and affect the environment, necessitating their control (Whetstone, 2005; Lancar and Krake, 2002). Management of water weeds in the VBL is a daunting task at the moment, primarily due to the ecological vulnerability of the VBL due to the low-lying nature and a complicated network of water bodies and canals, extensive below-sea-level paddy cultivation regions, human settlements along its entire bank, and cities and many townships in the adjacent areas. Hence, the task of managing water weeds in VBL requires synergy among government, non-government and support agencies, community-based groups, and the general public. The most successful way forward is for large-scale eco-restoration programmes to be created and implemented over longer periods, which may need effective enforcement or re-enactment of current regulations. Social awareness about the environmental status of VBL and the need to improve its overall ecological status through direct engagement at the government level, local governing agencies, community/organizational level and through all media would be very important to involve participation from all walks of life in water weed management. Also, educating school children about the status of their immediate aquatic environments by including it in the curriculum would be beneficial to develop an environment-responsible living culture in future and also to involve them in the ecosystem restoration process, which is inevitable to vulnerable systems like VBL. Long-term scientific research and monitoring programmes of water weed proliferation should be envisaged, and quantitative data on various aspects of the environment, including biodiversity, ecology, and socioeconomics, would be extremely beneficial for the future management of VBL, especially in a changing climate scenario (Sreejith, 2013). In VBL, water weeds management strategies have not reached farmers as efficiently as fertilisers and pesticides, and one of the main reasons is that water weeds cause hidden losses, which are often overlooked by farmers and local communities (Jayan and Sathyanathan, 2012). One of the major reasons for the unpopularity of cost-effective weed treatments is a lack of understanding of the losses due to weed proliferation and how to control them. The following are some weed management measures in the VBL considering the present environmental status and future scenarios in a changing climate.

(a) Presently, periodic removal of waterweeds in VBL using all available physical, chemical, and biological means can not be overlooked as an immediate resort, as most interior canals and water bodies are entirely choked. Due to the regrowth of water weeds from their fragmented vegetative parts and the germination of their dormant seeds, episodic weed biomass removal appears to be inefficient to eradicate them from the present level of infestation. Also, due to the interconnectedness of numerous water bodies and canals in the VBL, weed removal from isolated areas under the initiative of local government bodies has only very little desired effect. A better option is the concurrent removal of weed biomass from the entire VBL and even from its catchment areas periodically over longer time scales, which is a huge task. All supporting agencies, community-based groups, and the general public must be included in this process under the supervision of local government bodies with a state-level coordination and management mechanism. The removed water weed biomass must be buried scientifically to prevent it from becoming a source of new weed proliferation and to avoid the leaching of dangerous chemicals such as heavy metals from contaminating drinking water reservoirs, impacting animal life. Currently, especially during the SWM, a large amount of water weed biomass from the upstream is advected towards the sea via sea inlets, where it settles and piles up on the seashore's recreational beaches (Supplementary Material 12). This is a serious environmental concern that is currently being overlooked, particularly due to the high nutrient and heavy metal content of these water weeds (Imchen et al., 2017; Arunpandi et al., 2021). This problem needs to be thoroughly investigated and necessary mitigation measures implemented by authorities to remove the piled up weed biomass regularly and scientifically bury it to avoid nutrient and heavy metal leaching into the region's recreational beaches.

(b) It is clearly shown in this study that the long-term environmental deterioration, disruption of the hydrographic equilibrium, and the resulting stagnancy of water in the VBL have greatly fostered the spread of water weeds during the last few decades. Following the SWM season, the VBL 's upstream and flow-restricted canals become practically motionless, allowing water weeds to grow and proliferate, forming thick mats. Therefore, maintaining free flow in all of these inner water bodies is critical and the foremost requirement for controlling water weed proliferation in future. Further encroachment and reclamation of the VBL should be prohibited by law, and immediate corrective measures should be implemented where shoreline encroachment has disrupted the free flow of water. In the current dire situation, it appears promising that the open waters of VBL should be legally protected as a living entity, with adequate legal rights and any reclamation or encroachment on them is considered as a grave breach of the law. It is also critical to safeguard a tiny strip of land on the fringes of the complex network of water bodies in VBL as an 'ecotone' from further encroachment and unlawful resource exploitation. This study also summarised that the fragmentation of VBL waterbodies by the construction of landfilled roads should be unconditionally forbidden by law. Alternatively, elevated roads that do not block free water flow may be a preferable choice if roadways are so inevitable in certain regions. Wherever feasible, necessary corrective measures should be implemented on existing large landfilled roadways to allow free flow of water between fragmented water bodies on both sides.

(c) Saltwater barrages established in the VBL are undeniably a key promoting factor for the spread of water weeds, and their operation should be reconsidered holistically based on the sound scientific backing on the adverse ecological consequences they create. Removal of these barrages at this stage is impractical because they provide some important and essential services to the human population in the respective regions, such as preventing saline water intrusion into upstream freshwater reservoirs and paddy fields, and they also serve as bridge-cum-roadways, facilitating transportation between regions that would otherwise be disconnected (WISA, 2013; MSSRF, 2007; Kolathayar et al., 2021). Studies showed that saline water has a natural control over the water weeds currently dominating in the VBL. Imchen et al. (2018) showed that the most frequent water weeds in the VBL, *Eichhornia*, could only sustain a maximum salinity of up to 20 PSU, but even salinities lower than this might impede and disturb their normal growth as in freshwater. When it comes to the second most common water weeds in the VBL, *Monochoria*, Athira et al., (2019) found that water with 25 to 250 mg/L NaCl fully inhibited seed germination in experimental settings. In 2011, a team of experts looked into salinity and flood control scenarios in the VBL and suggested that it is feasible to keep the TB shutters open each day for a fixed period to allow saline water intrusion and mixing while reducing pollution accumulation in the upstream (WISA, 2013). This is a very futuristic proposal to allow some saline water intrusion and tidal flushing, but the salinity levels that should be allowed to rise upstream of the barriers should be decided on a more solid scientific basis so that they can at least inhibit, if not kill, the water weeds in the upstream of the VBL.

(d) Nutrient loading of VBL, by all means, must be greatly reduced by stringently implementing the existing laws and also through eco-friendly solutions. Based on scientific studies, optimise the use of chemical fertilisers and pesticides in agricultural areas, and restrict the use of excess nutrients that contribute to seepage into open water bodies of VBL (Indira Devi, 2007; WISA, 2013). Eco-friendly manures, as well as paddy rotational cropping and aquaculture, are preferable alternatives for reducing nutrient seepage from agricultural zones. There is also an urgent need to reduce the amount of nutrient-rich domestic and municipal sewage as well as industrial outfalls that are eutrophicating the VBL and supporting the proliferation of water weeds (WISA, 2013). It is vital to enforce strict waste treatment rules on houseboats, and there is an urgent need to provide clean sanitation facilities for the entire population living on the VBL 's banks. Massive livestock management in many sections of the VBL especially in the Kuttanad is another source of nutrient loading, since their faeces and butchering wastes are largely discarded into nearby water bodies. This element must be carefully considered and the residents should be provided with the required technical and financial assistance to dispose of all such domestic wastes appropriately without adversely affecting the fragile ecosystem of the VBL through eutrophication. No new industries should be permitted to build on VBL 's banks in the future, and existing industries should be under strict surveillance for wastewater disposal and be endorsed for eco-friendly pollution management plans.

(e) The siltation and shallowing of the VBL have many ecological effects over the long term, in addition to the chaos on human life, notably in the Kuttanad area. It reduces the water holding capacity of the VBL and results in heavy flooding of the low-lying areas, especially during the SWM and cyclonic depression events, which favour water weed propagation in various ways. The VBL's increasing shallowness and swampiness promote the growth of emergent plants such as *Monochoria* and *Limnocharis*, while regular flooding facilitates the spread of all weeds to a previously uninhabited area. As a result, feasible interventions to reduce siltation and flooding may have an indirect positive effect on restraining the water weed proliferation in VBL. Conservation of the catchment areas of the rivers that flow into the VBL, as well as increasing the storage capacity of several dams by removing massive amounts of silt settled in them over the many decades, and deepening of the VBL 's open water bodies are some of the possible options that must be considered based on sound water balance and environmental impact assessment studies conducted by professional agencies.

(f) Aquatic weed control through their biomass conversion into useful products is a great idea, and at present, the economic viability of various possibilities is the main impeding factor. To overcome this obstacle, the government should promote such attempts and facilitate incentives to develop and practice innovative methods of aquatic weed usage, for managing the aquatic weeds and restoring water bodies for extending their natural ecosystem services. Such an approach may facilitate many work opportunities for reducing rural village unemployment. To make better use of these resources, research should be focused on creating new methods of collecting and processing aquatic weeds in an eco-friendly manner. (g) Indeed, the integrative management of the proliferating water weeds in VBL require scientific planning and effective execution on time. First of all, there is a basic need to conduct a comprehensive survey to assess the extent of the proliferation of water weeds in the VBL. Ecological research focussing on different ways of the removal of weed biomass, as well as methods of economically using aquatic plans, should all need to be considered under the water weeds management plan for VBL. There is currently no unified administrative framework in place for coordinating law enforcement, conducting a scientific study on various ecological components of VBL, and acting as a support system to the government in sustaining the environment. In this context, the formation of a Vembanad Wetland Management Authority, comparable to the Chilika Development Authority in Odisha, India, would be a good idea for consideration to restore the environmental quality of VBL. This nodal institution should be tasked with coordinating integrated VBL management, and the authority's rationale, powers and functions, and governance structure may be formulated based on input from the stakeholders from many walks of life.

9. Conclusion

This study presents the long-term environmental and human causes and consequences of the extensive waterweed proliferation in VBL, A massive tropical Ramsar wetland on India's Southwest coast. The study showed that the widespread infestation of water weeds in the VBL adversely affected primary production, water quality, navigation, fishing activities, and many other socio-economic adversities. Also over the years, the uncontrolled water weed proliferation favours significant horizontal and vertical shrinkage of the VBL which will augment its faster succession into swamps. The major factors behind the alarming water weed proliferation in VBL are: (a) biological adaptations and competitiveness of the water weeds (b) upset of the natural hydrographical balance through the prolonged and extensive reclamation of the open waters, construction of saltwater barrages and numerous land-fill roads, all of which in one way or the other, fragmented the water bodies of the VBL increasing the stagnancy (c) mounting nutrient loading from unscientific fertiliser usage in agricultural lands and mounting domestic, municipal sewage and industrial wastes (d) lack of a natural enemy (grazer) of the water weeds proliferating in VBL, and (e) frequent floods that facilitate efficient dispersion mechanisms of the water weeds into the uninhabited areas. Even though various physical, chemical, and biological approaches are promising, adequate data on the long-term efficacy of each of these approaches is lacking. Given the current alarming waterweed proliferation in many sections of the VBL, as well as the region's vastness, an integrated waterweed management approach appears to be more promising. To manage the waterweed menace in the VBL, which negatively impacts the environment and inhabitants in a variety of ways, a large-scale ecorestoration programme is certainly required. In light of the current status and future climate change scenario and its effects, which have the potential to alter the current distribution and expand the extent of waterweed proliferation in the VBL, new legislation, its implementation, and constant surveillance, preferably under a dedicated administrative body, are considered necessary.

Declarations

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Availability of data and materials

The data sets used and/or analysed during the current study are available from the corresponding author on reasonable request through the Director, CSIR-National Institute of Oceanography, India.

Author Contributions

Jyothibabu, R and Balachandran, K.K - Conceptualization, literature collection and drafting. Sarath, S and Santhikrishnan, S., literature and data collection and drafting. Karnan, C., Arunpandi, N., Alok, K.T., Ramanamurty, M.V - literature survey,   scientific discussions and drafting,

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Competing interests

The authors declare that they have no competing interests.

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Figures

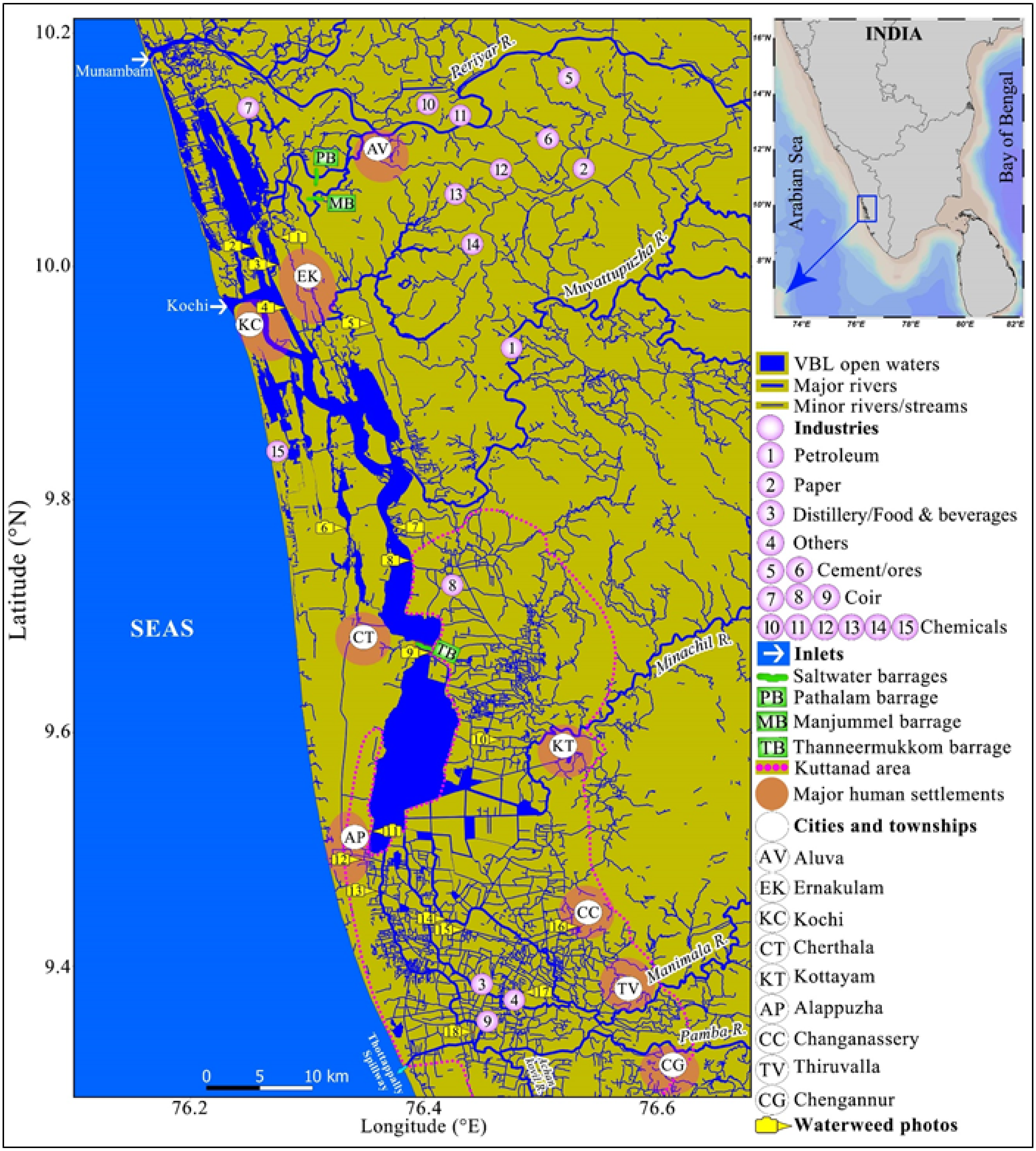

Figure 1

VBL and its rivers and complicated network of traversing canals. Important human settlements in townships, saltwater barrages, major industries, and vast paddy fields in the Kuttanad area are all depicted. The severity of the alarming waterweed proliferation in the VBLis presented in supplementary Figure 1, with photographs taken from various locations in different sections of the VBL and all those locations are indicated on this map with appropriate symbols and notations.

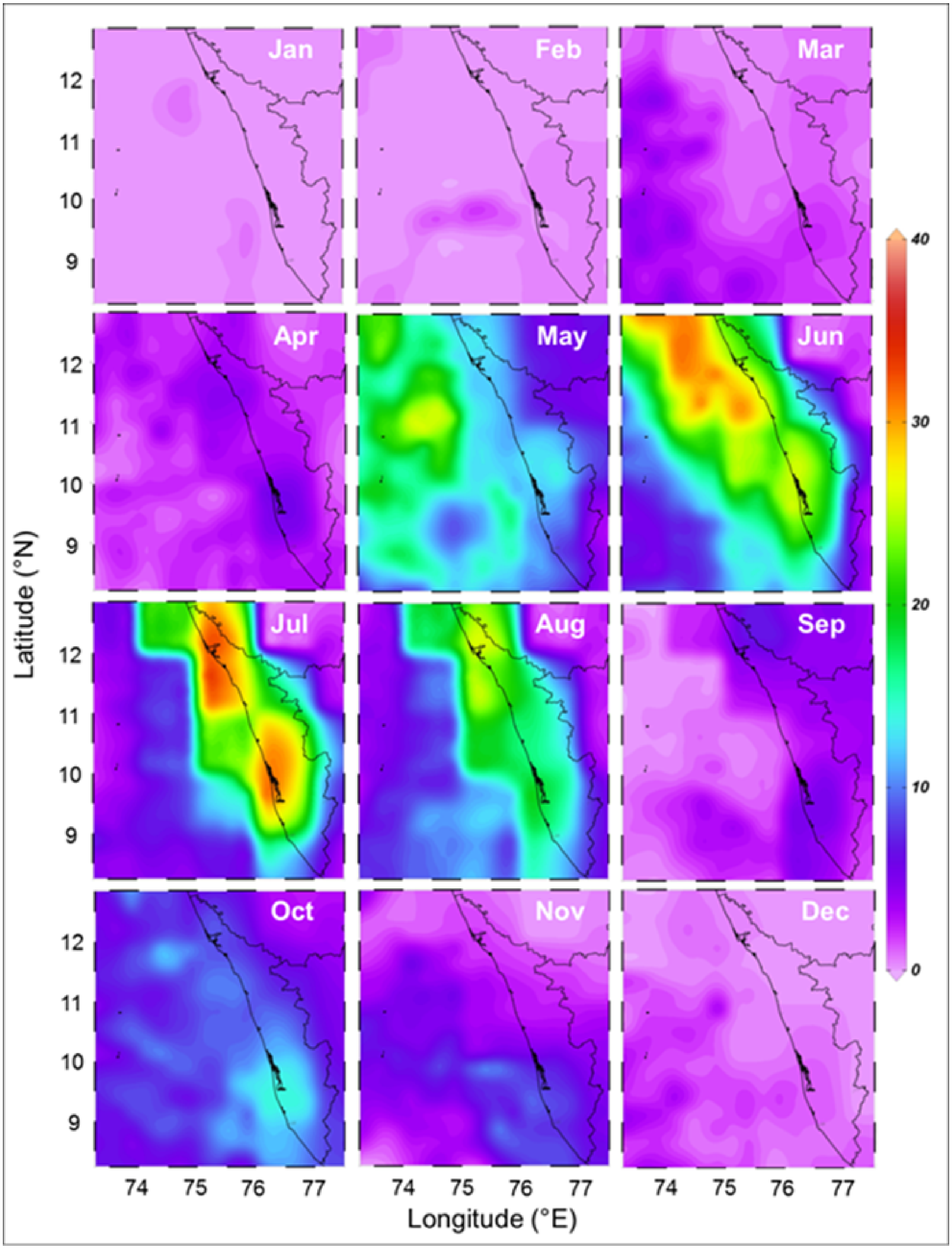

Figure 2

Seasonal rainfall pattern in the catchment area of the VBL that is represented as a white circle. A significant amount of the annual rainfall occurs in the region during the Southwest Monsoon (June to August).

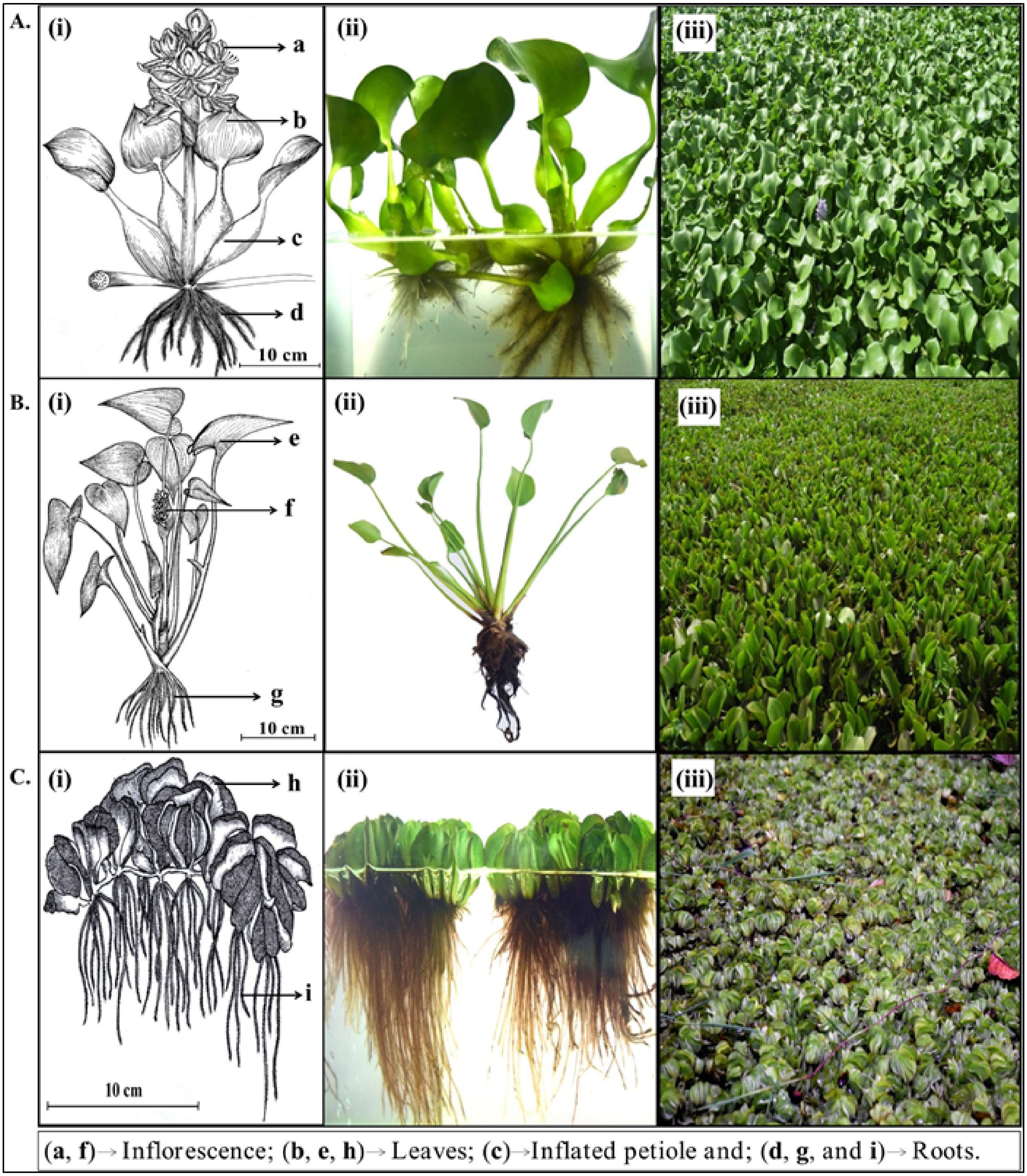

Figure 3

The most widespread water weeds in the VBL (A) *Eichhornia crassipes* (B) *Monochoria vaginalis* and (C) *Salvinia molesta.* Panels (i) scientific drawing, (ii) close up and (iii) field view.

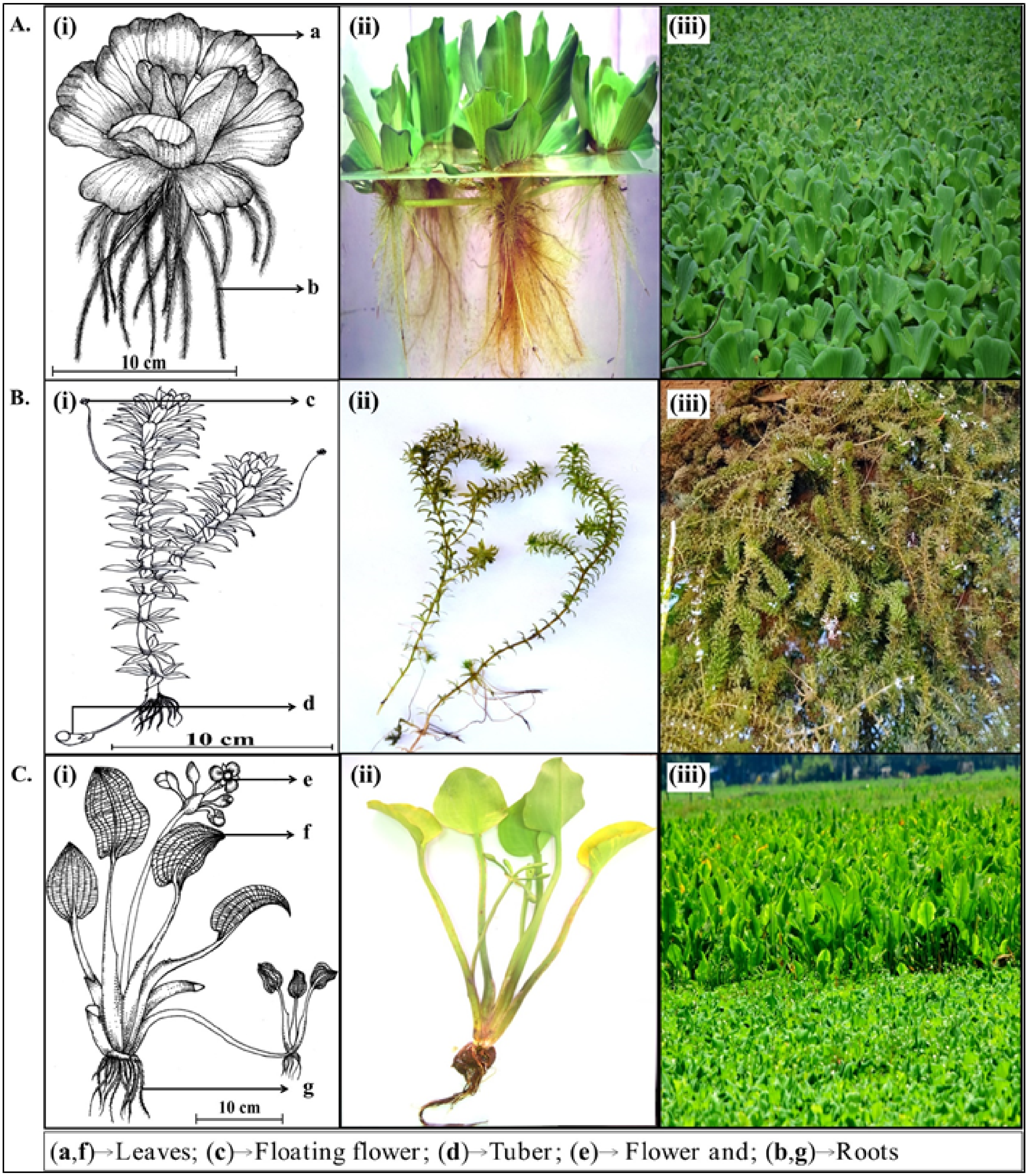

Figure 4

Water weeds dominating in certain sections of VBL **(A)** *Pistia stratiotes,* **(B)** *Hydrilla verticillata* and **(C)** *Limnocharis flava.* Panels (i) scientific drawing, (ii) close up and (iii) field view.

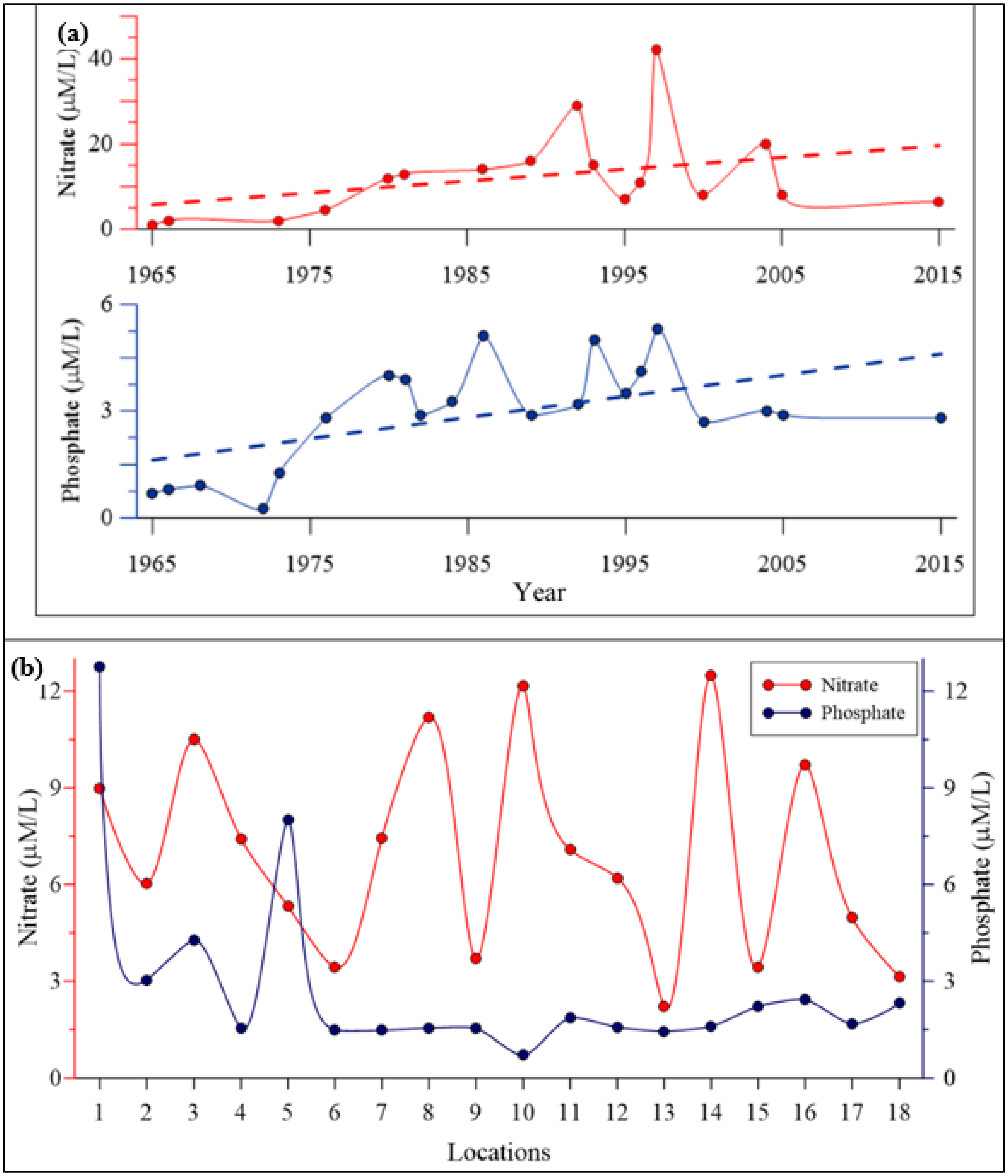

Figure 5

(A) Long-term eutrophication trend in the VBL's downstream (updated from Martin et al., 2012). The concentration of nitrate and phosphate and their long-term trends are presented. This is based on the publications of Qasim et al. 1969; Reddy and Sankaranarayan 1972; Qasim 1974; Sumithra et al. 1974; Joseph and Kunjukrishnapillai 1975; Remani et al. 1980; Gopinathan et al. 1984; Saraladevi 1986; Joy et al. 1990; Nair et al. 1990; Aravindakshan et al. 1992; Sheeba 2000; Balachandran 2001; Akram 2002; Qasim 2003; Selvaraj et al. 2003; Jyothibabu et al. 2006; Martin et al. 2008; Martin et al. 2010; Arunpandi et al., 2021). (B) The nitrate and phosphate concentration in the locations of the waterweed proliferations in the VBL photographed in Supplementary Material 1. The serial number of locations in x-axis correspond to the serial number of locations of the water weed photographs represented in Figure 1 and supplementary Material 1. The water samples for the nutrients were collected in clean glass bottles; Nitrate was analysed and analysed based on the standard procedure of Grasshoff, (1983).

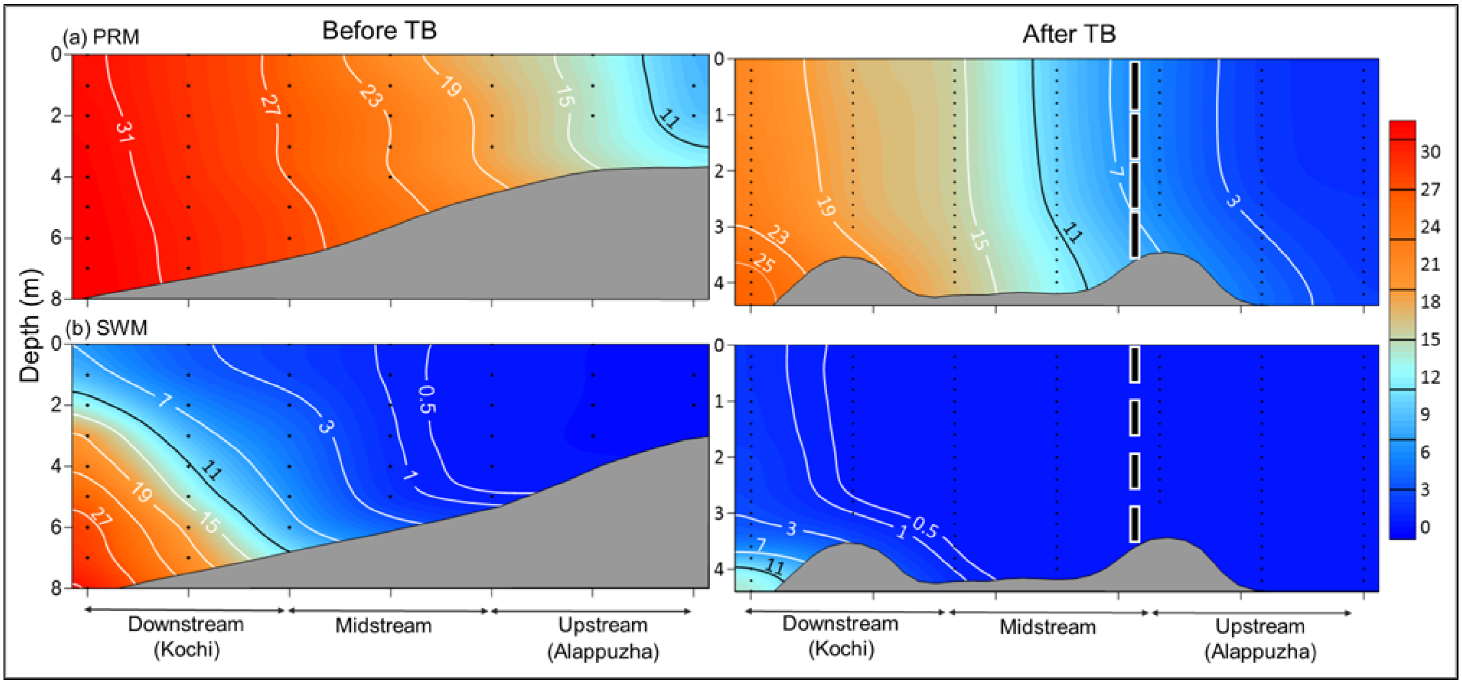

Figure 6

The impact of the flow restriction of Thannermukkom Barrage (TB) on the salinity distribution in the open waters of the VBL. During the PRM, the saline water intrusion into the upstream of the VBL is stopped by the closed shutters of the TB, creating stagnant freshwater zones beyond the reach of the tidal flushing from the sea inlets. Closed/open shutters of the TB during the PRM/SWM are represented by continuous/fragmented thick vertical lines, respectively.

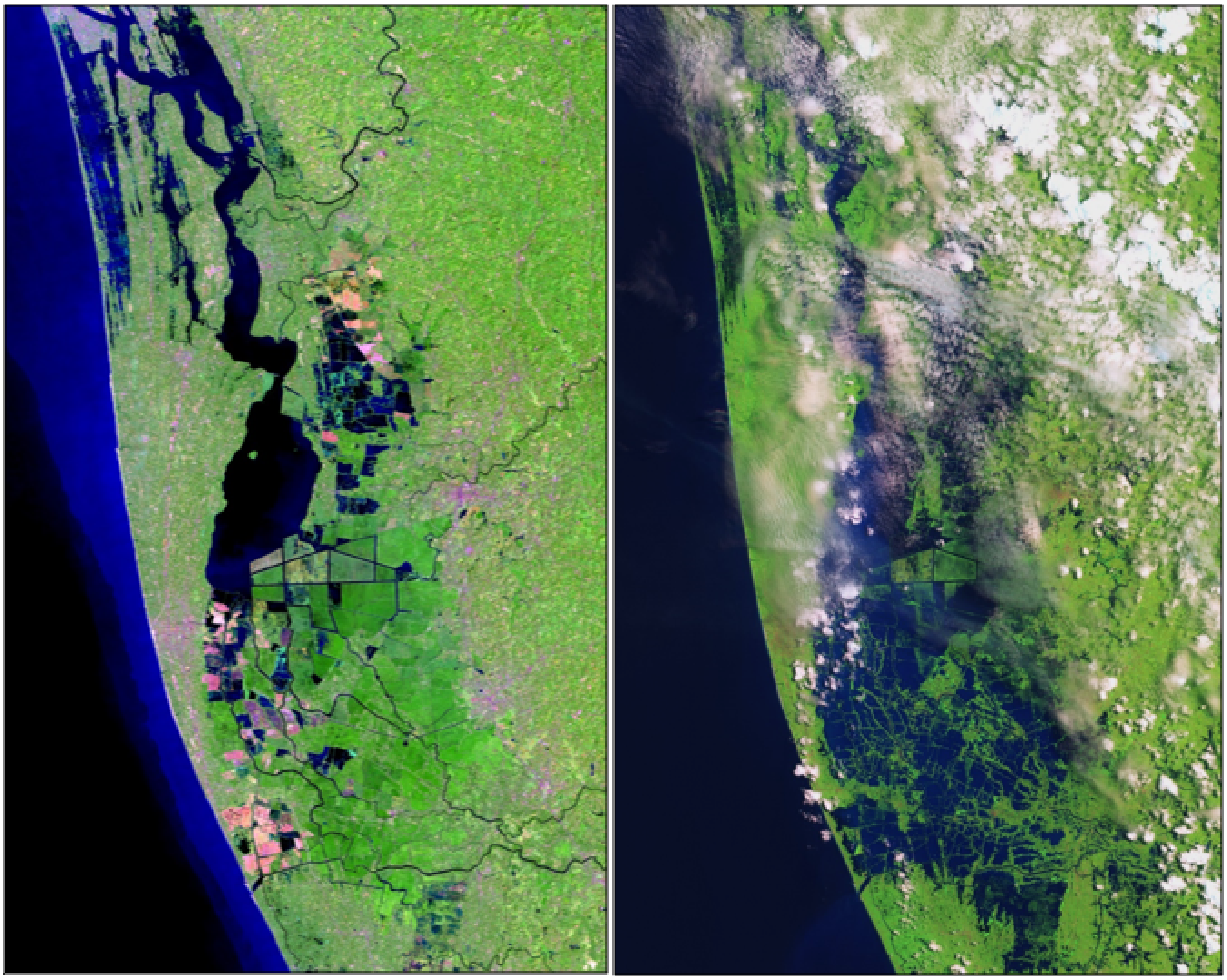

Figure 7

Satellite images showing the impact of flood in inundating the VBL into a continuous water body suitable for the propagation of waterweeds. Image (a) before and (b) during the flood of 2018 (https://earthobservatory.nasa.gov/images/92669/before-and-after-the-kerala-floods)

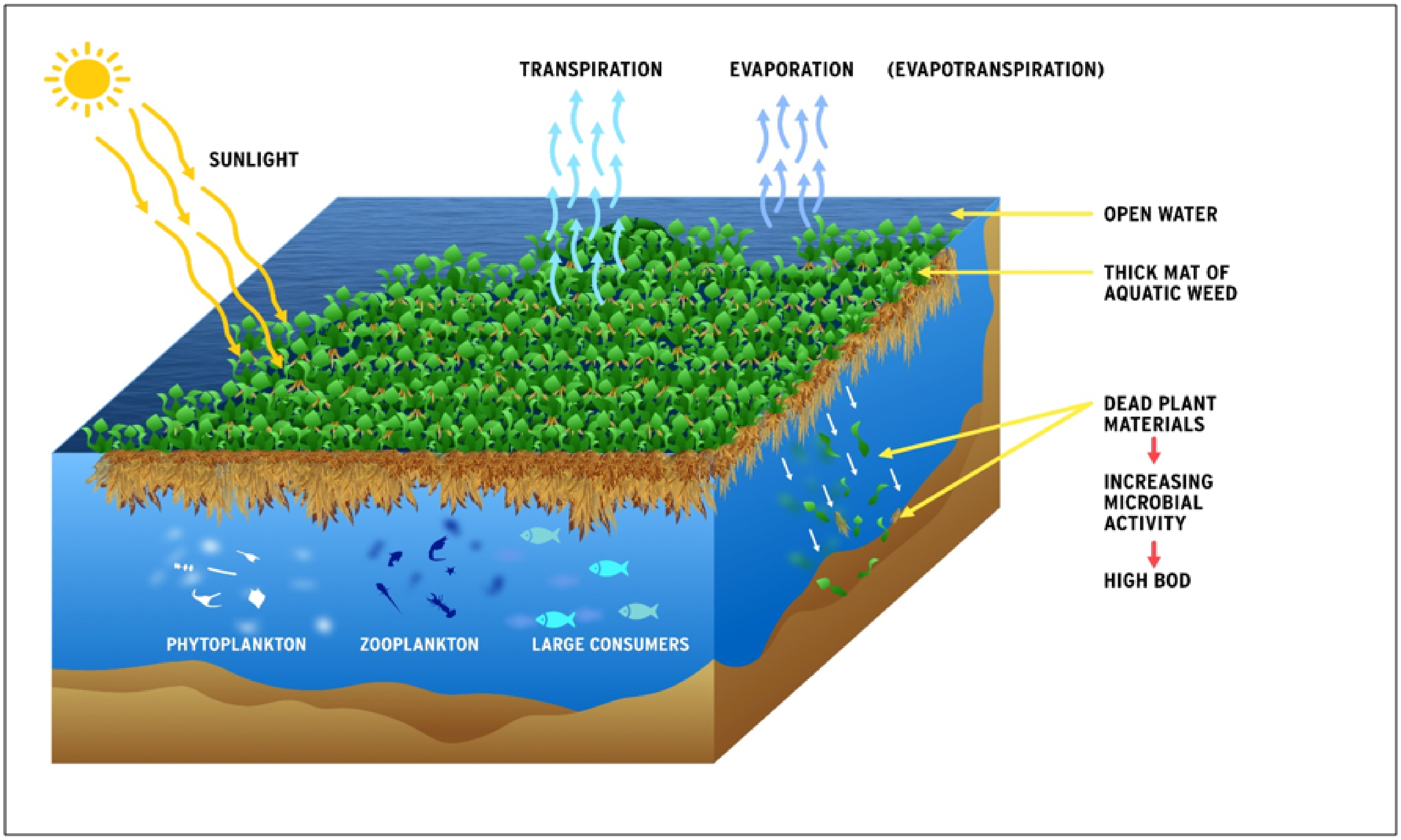

Figure 8

A summary diagram of the adverse effect of water weed proliferation on the ecology and the productivity of the VBL

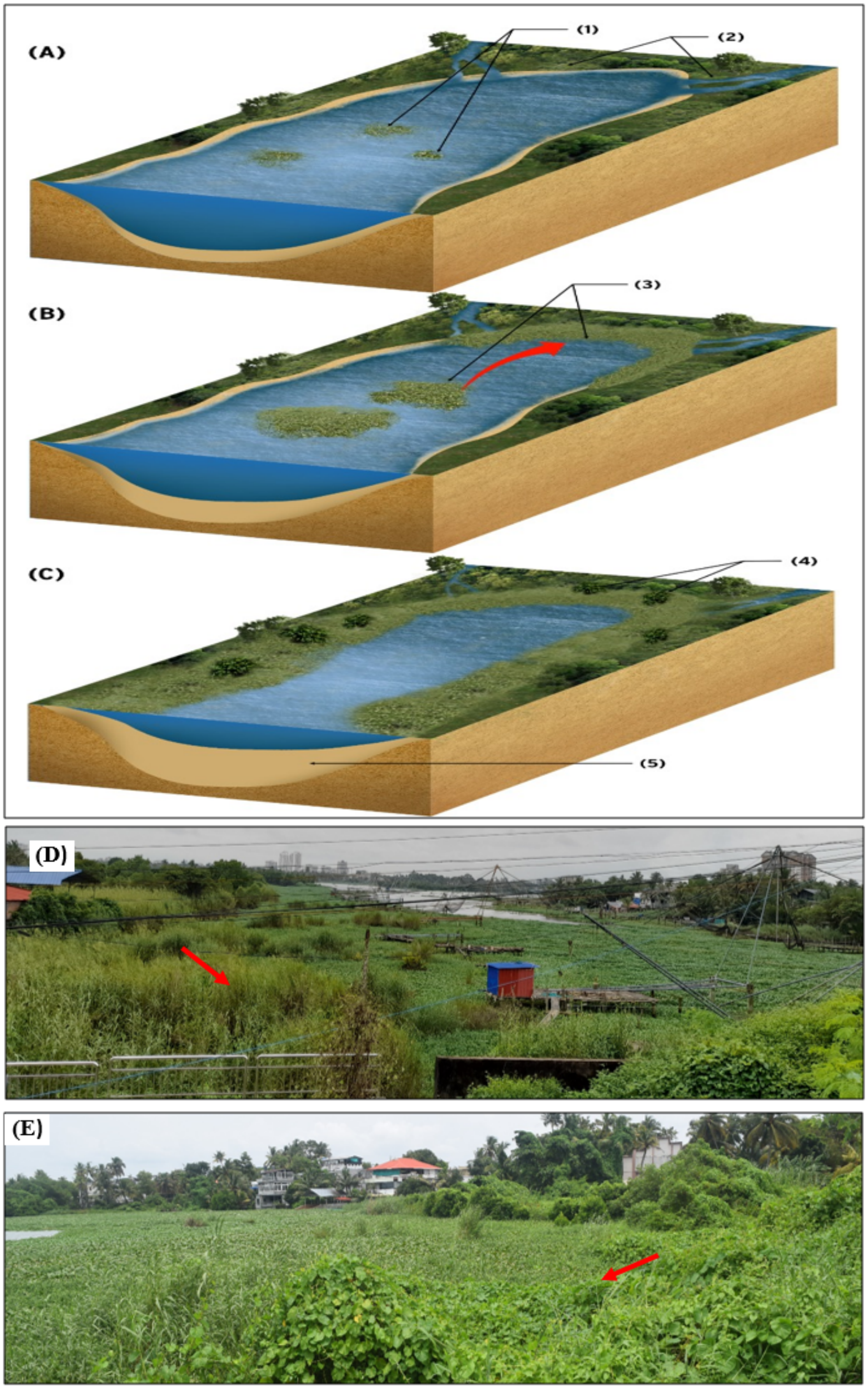

Figure 9

Faster succession of VBL due to water weeds proliferations on the shoreline. (A -C) schematic showing the different stages involved in the succession process. (A) floating water weed (B) attach to the shore line and (C) create swampy environments conducive for other semiaquatic and terrestrial plants to grow profusely. (D) and (E) are photographs of horizontal shrinkage of the VBL due to the accelerated succession by water weeds.

Supplementary Files

This is a list of supplementary files associated with this preprint. Click to download.

- SM1Severietyofwaterweedproliferation.docx
- SM10ACcanalblockagetoboats.docx
- SM11Interiorcanalblockages.docx
- SM12Settingwaterweedsontheseeashore.docx
- SM2Waterweedmenaceinmedia.docx
- SM3ImagesofSaltwaterBarrages.docx
- SM4WeedremovalACandpoorwaterquality.docx
- SM5SpreadofwaterweedsGBIF1.docx
- SM6AbandinedChinesenets.docx
- SM7Difficultytochinesenetsbarmouth.docx
- SM8Difficultytofishcages.docx
- SM9Trappingoffishermen.docx