Knowledge document for risk analysis of the non-native Curly Waterweed (*Lagarosiphon major*) in the Netherlands

by
J. Matthews, R. Beringen, F.P.L. Collas, K.R. Koopman, B. Odé, R. Pot, L.B. Sparrius, J.L.C.H. van Valkenburg, L.N.H. Verbrugge & R.S.E.W. Leuven

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Cover photo: High density of *Lagarosiphon major* in an urban pond in Soest, The Netherlands on August 13, 2010 (Photo: R. Pot)

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Summary

Curly Waterweed (*Lagarosiphon major*) is a member of a genus of plants that were all endemic to different parts of Southern Africa. *L. major* was first recorded in the Netherlands near the municipality of Soest around 2003 and has since spread to a number of locations in the southern and northern provinces. It has dispersed to a number of European countries and Australia and New Zealand, outside of its native range, and has been declared an invasive species in many of these countries. To support decision making with regard to the design of measures to prevent ecological, socio-economical and public health effects, the Netherlands Food and Consumer Product Safety Authority (Ministry of Economic Affairs, Agriculture and Innovation) has asked us to carry out a risk analysis of *L. major.*

A literature study was carried out to provide an overview of the current knowledge on the distribution and invasion biology of *L. major* and to support a risk assessment within the Dutch context. Literature data were collected on the physiological tolerances, substrate preference, colonization vectors, ecological and socio-economic impacts and potential measures for management of this species. The literature study was largely internet based with use of university libraries. Various academic and non-academic search engines and websites were used in a systematic search of the Web of Knowledge, Scopus, Google Scholar and in an analysis of information available to the Dutch public, Google.nl. A summary of the results of the literature study is given in the following paragraphs.

Introductions of aquatic plants across borders can be attributed to the trade in aquatic plants. The level of import of *L. major* to the Netherlands for use in aquaria and garden ponds has been shown to be in excess of that seen for other European countries and the plant is sold freely at garden centres and over the internet. A synonym for the Dutch common name, 'Gekroesde waterpest' is often used in the plant trade. The type of information available to the public via Google.nl differs depending on the search term used. Synonyms of the Dutch common name for *L. major* produced results that were either biased towards education, relating to the invasive nature of *L. major*, or its sale (e-commerce). A small proportion of hobbyists confess to the disposal of water plants into local watercourses. The limited distribution of *L. major* in and around urban areas and its use in ponds and aquaria suggests that voluntary introductions by the public may be the major pathway through which *L. major* reaches the freshwater network. However, wider dispersal away from these isolated points of introduction appears to be limited in the Netherlands. This is despite the ability of *L. major* to reproduce vegetatively through fragmentation and the potential transfer of these fragments to new locations via water current and other dispersal vectors e.g. boats, fishing equipment, weed harvesters and vehicles. Absence of water current and dispersal vectors at areas of introduction have been put forward as reasons why wider dispersal has not occurred within the Netherlands. The limited current distribution of *L. major,* despite it being present for at least 9 years in the Netherlands, suggests that

the dispersal potential and invasiveness of *L. major* may be limited within the Dutch context.

The colonisation of high conservation habitats has, at the time of writing, not occurred within the Netherlands. Introductions have been limited to urban areas and rural areas bordering on these urban areas. However, a potential high conservation value habitat in which *L. major* may appear is the EU Habitats Directive type H3150 (Natural eutrophic lakes with Magnopotamion or Hydrocharition-type vegetation). This habitat type features species like *Stratiotes aloides*, *Utricularia vulgaris* and *Hydrocharis morsus-ranae*.

The impacts of *L. major* on native species and ecosystems within the Netherlands is currently limited due to its limited distribution. In other countries impacts on native species and the local ecosystem have been considerable. Changes in habitat conditions due to *L. major* may cause species replacement. For example, in Ireland characteristic dense meadows of charophyte vegetation, mixed with tall stands of *Myriophyllum spicatum, Elodea canadensis* and a range of *Potamogeton* species have been lost at Lough Corrib due to *L. major* invasion. Habitat changes resulting from *L. major* colonisation also favour certain fish species. Salmonids and Trout species that favour open water may be replaced by cyprinids and other species that prefer the shelter that dense stands of macrophytes provide. Changes in macroinvertebrate species composition have also been observed. *L. major* can form dense stands of vegetation over a wide area blocking light, encouraging anoxic conditions within substrates and altering nutrient cycling and physico-chemical conditions. Restriction to water-flow may reduce the discharge efficiency of colonised water bodies encouraging flooding and changes within food webs may occur due to changes in species abundance and composition. No evidence of transmission of diseases and parasites or genetic effects due to hybridisation were found during the literature study.

In general, the height and complexity of the plant canopy in beds of non-native species results in a physical change in habitat that appears to provide more habitat for zoobenthic prey, more resting area for benthic fish such as the common bully (*Gobiomorphus cotidianus*), and greater refuge from top predators than in native beds. *L. major* and other native species maybe the only aquatic plants that can tolerate the conditions present and removal of these plants could further degrade the habitat.

If active control of *L. major* is required, as in the village Emmer-Erfscheidenveen, the Netherlands, the best method is removal using harvesting machinery e.g. mowing baskets or harvesting boats, and the prevention of fragment spread. The best method to prevent spread of the species seems to be as reticent as possible with management. At most of the known sites in the Netherlands. the plants did not spread when no additional management measures were introduced.

Once the plants have established, eradication is very difficult. The best option is to isolate the local populations and then wait for their disappearance. At the very least a natural lowering of fitness and abundance may be expected.

1. Introduction

1.1. Background and problem statement

Curly Waterweed (*Lagarosiphon major*) is a member of a genus of plants that are all endemic to different parts of Southern Africa. *L. major* is a well-defined species and is the only species of the genus *Lagarosiphon* that has been cultivated and introduced elsewhere (Symoens & Triest, 1983). *L. major* was first recorded in the Netherlands near the municipality of Soest around 2003 (Valkenburg & Pot, 2008). Over the past decade, this plant species was also recorded at locations in the southern and northern provinces. At the start of this project, there was a lack of knowledge regarding the pathways for introduction, vectors for spread, key factors for establishment and invasiveness, and (potential) effects of *L. major* in the Netherlands.

To support decision making with regard to the design of measures to prevent ecological, socio-economical and public health effects, the Netherlands Food and Consumer Product Safety Authority (Ministry of Economic Affairs, Agriculture and Innovation) has asked us to carry out a risk assessment of *L. major.* The present report reviews available knowledge and data in order to perform a risk assessment of the species.

1.2. Research goals

The major goals of this study are:

- To describe the species and habitat characteristics of *L. major.*
- To describe the global distribution and to analyse the current spread of *L. major* in the Netherlands.
- To identify the key factors for dispersal (pathways, vectors, invasiveness) and successful establishment of *L. major*.
- To assess (potential) ecological, socio-economical and public health effects of *L. major* in the Netherlands, taking into account the impacts of this species in other geographical areas.
- To summarize available risk classifications of *L. major* in other countries.
- To review possible management options for control of spread, establishment and negative effects of *L. major*.

1.3. Outline and coherence of research

The coherence between various research activities and outcomes of the study are visualised in a flow chart (Figure 1.2). The present chapter describes the problem statement, goals and research questions in order to identify key factors for the dispersal, establishment, effects and management of *L. major* in the Netherlands. Chapter 2 gives the methodological framework of the project and describes the literature review, data acquisition and field surveys. Chapter 3 describes the identity, taxonomical status and reproductive biology of the species and briefly mention differences with visually similar species. The habitat characteristics are summarized in chapter 4. The geographical distribution and trends in distribution in the Netherlands, including relevant pathways and vectors for dispersal are given in chapter 5. Chapter 6 analyses the ecological, economic and public health effects of the species. Formal risk assessments and available risk classifications are summarized in chapter 7. Chapter 8 describes the scope of management options and focuses on prevention, eradication measures and control of the species. Finally, chapter 9 draws conclusions and gives recommendations for management and further research. Several appendices with raw data and background information complete this report. The report will be used as background information for an expert meeting in order to assess the dispersion, invasiveness, (potential) risks and management options of species in the Netherlands (Risk analysis).

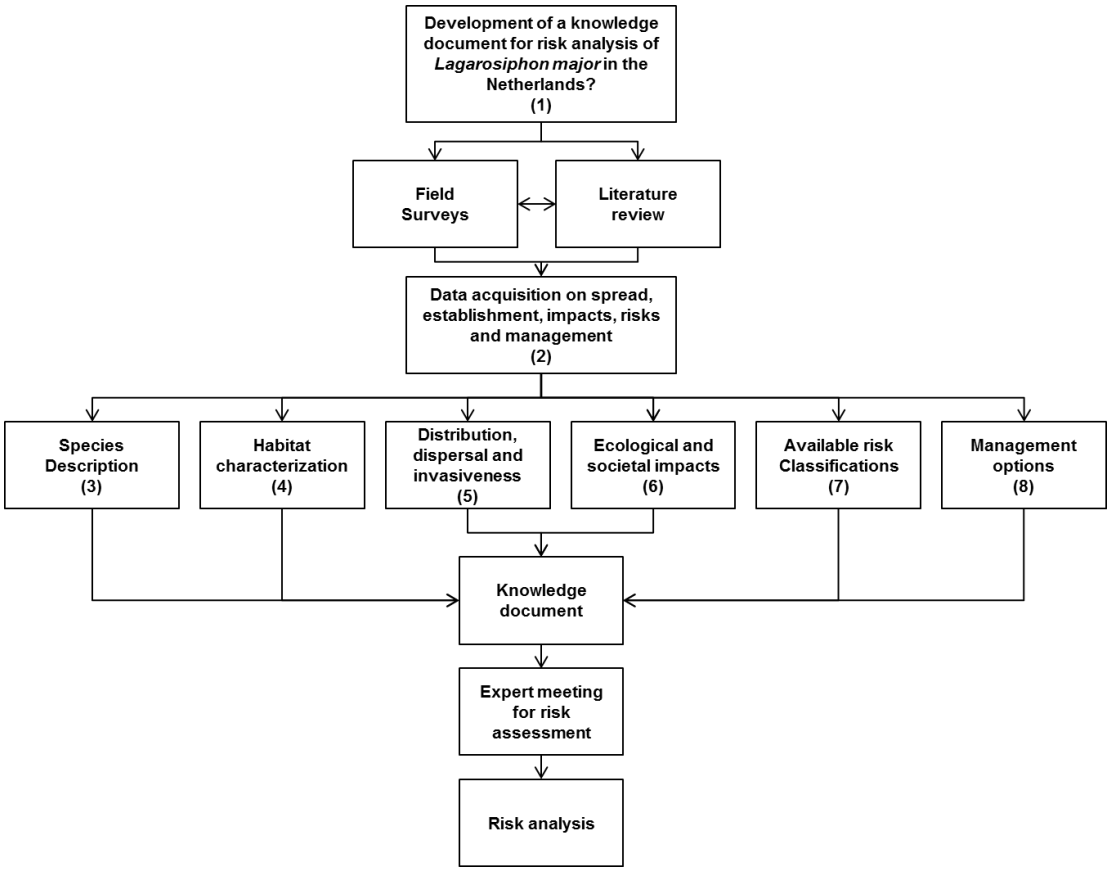

Figure 1.2: Flow chart visualising the coherence of various research activities in order to develop a knowledge document for risk analysis of Curly Waterweed (*Lagarosiphon major*) in the Netherlands. Chapter numbers are indicated in brackets.

2. Materials and methods

2.1. Literature review

A literature study was carried out to provide an overview of the current knowledge on the distribution and invasion biology of Curly Waterweed (*Lagarosiphon major)*. Literature data were collected on the physiological tolerances, substrate preference, colonization vectors, ecological and socio-economic impacts and potential measures for management of this species. Our search was largely internet based with use of university libraries. Various academic and non-academic search engines and websites were used in a systematic search of the Web of Knowledge, Scopus and Google Scholar. All search results were examined for the Web of Knowledge and Scopus while the first 50 results were examined for Google Scholar due to the decreasing relevance of search results returned using this search engine. Search terms used to carry out the literature study were: *Lagarosiphon major*, *Lagarosiphon muscoides*, *Elodea crispa*, 'Verspreidbladige Waterpest', 'Inlandse Waterpest', 'Gekroesde Waterpest', African Elodea, Curly Waterweed, African Waterweed, Oxygen Weed, Curly Water Thyme and Submerged Onocotyledon.

All the articles found during the literature search were assessed on their relevance and, when useful, added to the database. The database consisted of the first author followed by the year and the title of the article. Besides the article the search engine and search term used to find the specific article were also added. Then two keywords for the specific article were added to the database, which allowed specific searches of certain subjects. A short description of the content of each article was given, as well as the scientific status (peer reviewed, grey or anecdotic paper). The availability of each article was also analyzed since not all articles were available in the libraries of Dutch universities or in the electronic public domain. Finally, the date of the search was indicated. The excel-file is available on request and contains all the articles acquired through the literate search.

To analyse the perception that the general public have of *L. major* and give an insight into its availability from retailers an analysis of search engine hits via Google.nl was performed. The first 50 websites found via a Google.nl search were categorized according to their content. Categories comprised regulatory, educational, retail and hobbyist websites and the number of websites contained within each category was recorded. Google was searched using the term *Lagarosiphon major,* and the Dutch common names 'verspreidbladige waterpest' and 'gekroesde waterpest'. Belgian websites were omitted as it was assumed that Dutch people would focus on retail websites in the Netherlands. Additionally, websites that contained names not referring directly to a species e.g. where only waterpest was mentioned, were omitted.

2.2. Data acquisition on current distribution

The distribution data originate from the National Database Flora & Fauna (NDFF). These data are complemented with data of herbarium specimens in the Q-bank

Invasive Plants database (http://www.q-bank.eu/Plants/) and recent recordings on the websites www.waarneming.nl and www.telmee.nl.

2.3. Additional field surveys

On Jun 27, 2012 field surveys at three locations (Emmer-Erfscheidenveen, Mussel-kanaal, Ter Apel) were performed (Appendix 1). All these sites were situated in the south-east of the province of Drenthe and the adjacent part of the province of Groningen, the Netherlands. At each site plants were collected for herbarium specimens and DNA barcoding. Population size was estimated and the vegetation was described with a Tansley survey, using the following abundance / dafor codes: d: dominant; a: abundant; f: frequent; o: occasional; r: rare. The growth form of each species was described using the following codes: d: floating; e: emergent and s: submerged. Data collected were species, location, date of field search, coordinates, water depth (cm), transparency / Secchi depth (cm), width of water body (m), water flow, water type, surface area covered by non-native species (m^2), number of individuals/shoots and phenology.

At each site water samples were taken and at the laboratory the pH and alkalinity of the water was measured, using a ABU901 Autoburette in combination with TitraLabtm 80 (Radiometer, Copenhagen). Supplementary samples of both sediment and water were stored in a refrigerator for further analysis.

3. Species description

3.1. Nomenclature and taxonomical status

Curly Waterweed (*Lagarosiphon major*) is a member of the Family Hydrocharitaceae and native to southern Africa (Obermeyer, 1964; Symoens & Triest, 1983). An overview of taxonomy, common names found in the Netherlands and the United Kingdom, the native range of *L. major* and similar species is given in table 3.1.

Table 3.1: Nomenclature and taxonomical status Curly Waterweed (*Lagarosiphon major*).

Scientific name:	
Lagarosiphon major (Ridley) Moss, 1928	
Synonyms:	
Elodea crispa *Lagarosiphon muscoides* Harvey, 1841 *Lagarosiphon muscoides* var. *major* Ridley, 1886	
Taxonomic tree	
According to CABI (2012): Domain: Eukaryota Kingdom: Plantae Phylum: Spermatophyta Class: Monocotyledonae Order: Hydrocharitales Family: Hydrocharitaceae Genus: Lagarosiphon Species: *Lagarosiphon major*	According to Mabberley (2008) Domain: Eukaryota Kingdom: Plantae Phylum: Tracheophyta Class: Spermatopsida Order: Alismatales Family: Hydrocharitaceae Genus: Lagarosiphon Species: *Lagarosiphon major*
Preferred Dutch name:	
Verspreidbladige waterpest	
Other Dutch names:	
Gekrulde waterpest, Gekroesde waterpest	
Preferred English name:	
Curly Waterweed	
Other English names:	
African Elodea, African Curly Leaved Waterweed, African Oxygen-weed, African Waterweed, Coarse Oxygen Weed, Curly Water Thyme, Fine Oxygen Weed, Lagarosiphon, Oxygen Weed, Oxygen-weed, South African Oxygen Weed, Submerged Onocotyledon	
Native range:	
Zimbabwe, South Africa	
Visually similar species:	
Elodea nuttallii, Elodea canadensis, Hydrilla verticillata, Egeria densa	

Sources: CABI (2012); Mabberly (2008); www.nederlandsesoorten.nl.

The preferred English name of *Lagarosiphon major*, Curly Waterweed, is derived from Stace (1997) and is the prevailing name in UK and New-Zealand. In literature, it is the name that is predominantly applied and is not used to name any other macrophyte species. The addition 'African' is only suitable for the second most used name, African elodea. This is because Elodea is a genus originating mostly in North American that includes several species, and is both closely related to Lagarosiphon and similar in habit. The official Dutch name is derived from Van Valkenburg & Pot (2008) and is accepted by the National Herbarium and the Dutch Species Catalogue (http://nederlandsesoorten.nl). The scientific name, *Lagarosiphon major*, is generally accepted as the legal scientific name (Symoens & Triest, 1983). Other names mentioned are found in regional publications and are used in the trade of aquarium and pond plants. The name *Elodea crispa* has no scientific reference.

3.2. Species characteristics

L. major is a perennial, submerged, rhizomatous aquatic plant with leaves that alternate spirally along the stems (Bowmer *et al.,* 1995; Figures 3.1 and 3.3).

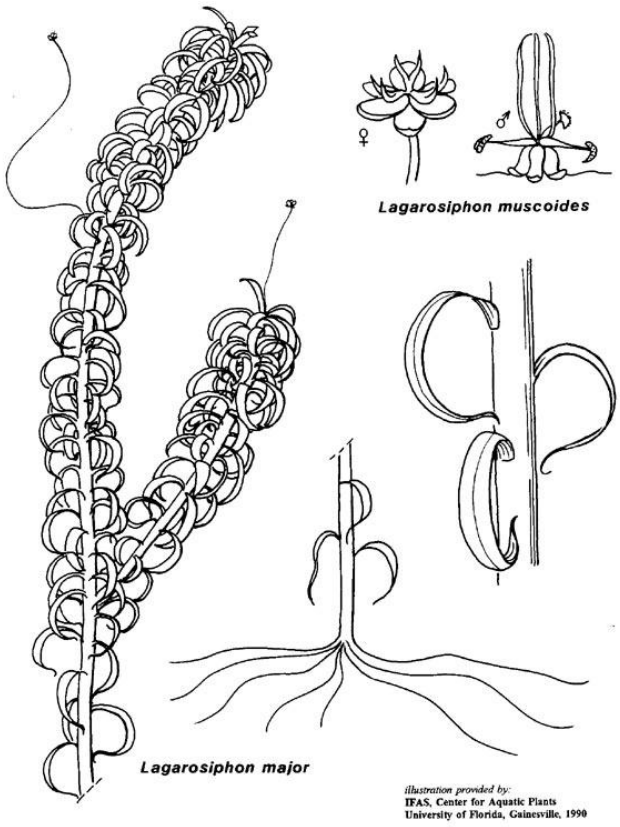

Figure 3.1: Identification of Curly Waterweed (*Lagarosiphon major*) (UFL-CAIP, 2001).

The leaves are minutely toothed, 5-20 mm long, 2-3 mm wide and generally have tapered tips that curve down towards the stem (Caffrey & Acavedo, 2007). They often crowd towards the apex of the stem (Figure 3.2). In low alkalinity waters the leaves can appear straight (Australia Natural Heritage Trust, 2003). The brittle, sparsely branched stem can grow to up to 20 feet long, is 3-5 mm in diameter and curves like a 'J' towards the base. The female flower is very small, with three transparently white/pink petals that

are attached to a filament-like stalk above the water's surface (Figure 3.1). The free floating male (staminate) flowers have a sail composed of 3 staminodes (sterile stamens) and are moved by wind or currents (Centre for Ecology and Hydrology). The fruit is a beaked capsule, containing approximately nine seeds, each seed being approximately 3 mm long (UFL-CAIP, 2001). At the nodes, single, pale adventitious (branching from the stem) roots are produced (Figure 3.1). These trail in the water and can aid with nutrient uptake for the plant. Additional adventitious roots and pseudo-rhizomes attach the plant to the substrate. These pseudo-rhizomes also act as over wintering organs. The stems are sparsely branched until they approach the water surface. There, they branch repeatedly to produce extremely dense mats on and below the surface.

Figure 3.2: Dense vegetation of the Curled Waterweed (*Lagarosiphon major*) in a ditch near Ter Apel in the Netherlands (Photo: R. Pot).

3.3. Differences with visually similar species

A number of species are visually similar to *L. major* and it is therefore important to differentiate these species in order to prevent mis-identification. The following information should be taken into account when identifying *L. major*:

- The leaves of *L. major* occur in alternate spirals or pseudowhorls of 3-4 (Figure 3.3), rarely in whorls; those of the similar species occur in whorls of 3 (*Elodea*) or 4-5 (*Egeria, Hydrilla*).

- The leaves of *L. major* are rigid and keep their shape when taken out of the water, leaves of similar species are supple and collapse when taken out of the water; plant tops often emerge through the water surface by a few mm.

- The leaves at the tops of *L. major* are similarly curved as the lower leaves, leaves of the similar species are usually erect towards the top.

Figure 3.3: Detail photo of Curly Waterweed (*Lagarosiphon major)* highlighting pseudowhorled leaf pattern (Caffrey & Acavedo, 2007; Photo reproduced with permission of J. Caffrey, Inland Fisheries Ireland).

3.4. Reproduction

Outside its South African native range, only female plants are known (Cook, 1982; National Botanic Gardens, 2007) and all reproduction is by fragmentation or vegetative reproduction. Neither the male flower, which floats freely to the surface, nor fruit or seeds have been recorded outside of its native range. Reproduction and dispersal are facilitated by the detachment of small fragments and lateral branches that subsequently become rooted (Centre for Ecology and Hydrology, 2004).

4. Habitat characteristics

4.1. Habitat description

In general Curly Waterweed (*Lagarosiphon major*) displays a wide tolerance to different habitats. In a recent assessment of the status of seven invasive plants in New Zealand, the Large-flowered Waterweed (*Egeria densa*) and *L. major* had spread into at least 32 and 38 new localities from 2000 to 2008, respectively, spanning wide trophic, altitudinal and temperature ranges (de Winton *et al.,* 2009). *L. major* achieves its maximum vegetative expression in clear, still water. It is tolerant of low nutrient conditions, but grows best in hard water with a good nutrient supply (Caffrey & Acavedo, 2007). Research conducted in a number of New Zealand lakes has shown that the rate of growth of *L. major* does not necessarily correlate with the trophic status or water chemistry of the waterbody (Brown & Dromgoole, 1977). However, in lakes with accelerated eutrophication and severely decreased water clarity, *L. major* abundance declines (Coffey & Clayton, 1988). Inorganic carbon (as free CO_2), inorganic nitrogen and phosphorous are the most important factors in controlling plant size in *E. canadensis* and *L. major* (Riis *et al.,* 2010). In conjunction with pH, *L. major* can survive in high alkalinity conditions as well (Invasive species compendium). *L. major* is sensitive to wave action and wind, preferring to grow in sheltered sites or in reed beds (Caffrey & Acavedo, 2007). Reed beds trap floating plant fragments and provide shelter for subsequent establishment and growth. A study of Lough Corrib, an ecologically important Irish lake invaded by *L. major*, indicated that the plant was relatively widespread in the upper and middle lakes, particularly in sheltered, shallow bays and littoral areas. The plant was absent from rocky or boulder strewn locations within the lake and especially abundant where deep deposits of fine silt and organic mud accumulate. The preference of *L. major* for sandy substrates was also observed by Clayton *et al.,* 1981 and Chapman *et al.,* 1971. However, *L. major* is also able to establish on more coarse-grained substrates and small stands of the plant have also been recorded growing in sandy areas, where the amount of organic mud and silt is minimal (Caffrey & Acavedo, 2007).

In the Netherlands, during winter, there is a strong chance that ice will form. This has consequences for *L. major* living in turbid water as much of the biomass lies in the surface layer under this type of condition. Plants have to re-grow portions that are lost due to ice damage (Van Valkenburg, unpublished results). Experiences from the UK show that *L. major* tends to survive over-winter in southern areas of Britain. Further north, in colder areas, the plant mass collapses, but never dies down completely (Centre for Ecology and Hydrology 2004).

Table 4.1 gives an overview of the physiological tolerances of *L. major* identified during the literature search.

Table 4.1: Physiological conditions tolerated by Curly Waterweed (*Lagarosiphon major*).

Parameter	Data origin	Physiological tolerance	Reference
Depth (m)	International	0.12 - 6.6[b]	Coffey & Wah (1988); Global Invasive Species Database (2007); Centre for Ecology and Hydrology (2004); Schutz (2008); Caffrey & Acavedo (2007); Chapman *et al.* (1971)
Temperature (°C)	International	10-25 (18-23 optimal)	Dutartre (1986); Australia Natural Heritage Trust (2003); GB Non-Native Species Secretariat (2011)
Temperature *frost damage* (°C)	International	-1[a]	Bannister (1990)
Alkalinity (10^{-3} eq/l)	The Netherlands	1.15-1.74[d]	This study
pH	The Netherlands	6.5-7.0[d]	This study
pH	International	10.4[c]	Centre for Ecology and Hydrology; CAPM-CEH (2004); Stiers *et al.* (2011)
Light intensity (micro einsteins/m^2/h)	International	600 optimal	Schwarz & Howard-Williams (1993)
Nitrate (mg/l)	International	1.05	Schutz (2008)
Phosphate (mg/l)	International	0.33	Schutz (2008)

[a]: Lowest air temperature where no damage occurred (leaves exposed to air); [b]: Non-light limited environments; [c]: maximum for bicarbonate uptake; [d]: See appendix 1 for results obtained from fieldwork.

4.2. Associations with other species

At the visited sites in the Netherlands, *L. major* was accompanied by species like *Hydrocharis morsus-ranae*, *Lemna minor*, *Glyceria maxima*, *Sagittaria sagittifolia*, *Ceratophyllum demersum*, *Potamogeton natans*, *Spirodela polyrhiza* and on a single site by *Utricularia vulgaris* and *Stratiotes aloides* (Appendix 1).

5. Distribution, dispersal and invasiveness

5.1. Global distribution

Curly Waterweed *(Lagarosiphon major)* has spread from its indigenous habitat in South Africa to Australia and New Zealand and widely throughout Western Europe. Figure 5.1 gives an overview of its current world distribution. It should be noted that a single record of *L. major* maybe enough to categorise a country or state as colonised.

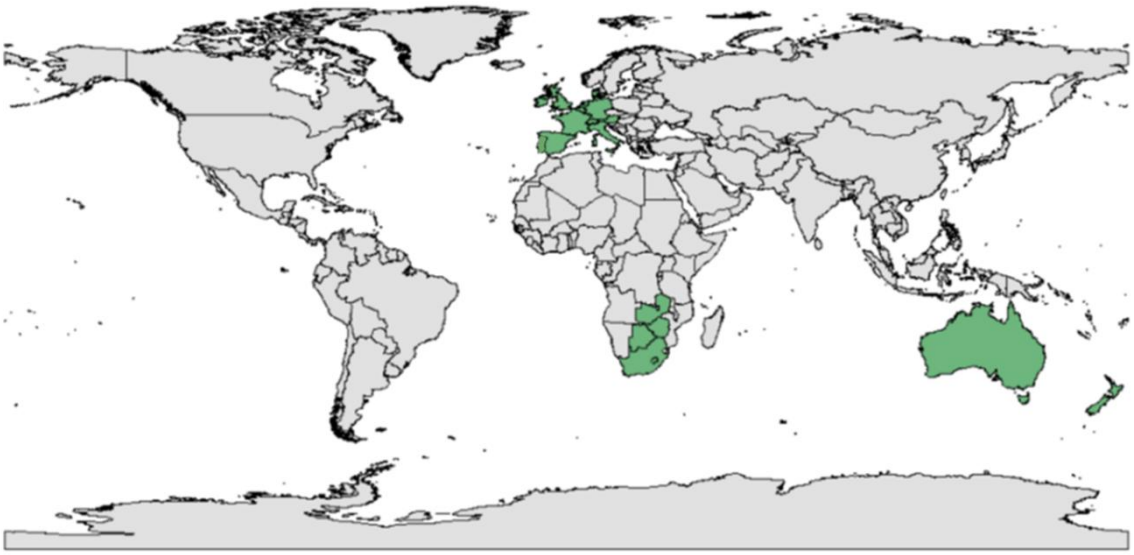

Figure 5.1: Global distribution of Curly Waterweed (*Lagarosiphon major*) based on published sources (www.q-bank.eu).

5.2. Current distribution in the Netherlands

5.2.1 Geographical distribution and trends in range extension

L. major was first recorded around 2003 in ditches in Soest (Valkenburg & Pot, 2008). The distribution looks erratic, with few grouped kilometre squares (Figure 5.2). Some locations are, however, remotely interconnected by rivers and canals, such as in Drenthe and Groningen. In some cases the plant may have been overlooked in between the known stands. *L. major* grows in stagnant or slow-flowing water at depths between 60-140 cm. At some sites the water is very turbid (Secchi disk readings less than 25 cm). All sites are situated in urban areas, although in Drenthe some sites are situated in rural areas ('veenwijken') located close to urban areas.

In the ditches in Soest the plant population persisted for 9 years (A. Aptroot, personal communication). The plants survived last two, relatively severe winters in shallow water (30-70 cm) with almost no signs of damage. During the summer of 2012 the plants showed a strong growth. In some other areas, *L. major* has been present for a period of at least 5 years. In June 2012 *L. major* was observed at Emmer-Erfscheidenveen, in the Musselkanaal and at Ter Apel (Appendix 1). In Ter Apel the

plants were only found in 2008 in high density (Figure 3.2 and 6.1). The same year the plants were removed partly in late summer to maintain the drainage function of the water body. Since 2009 the density of *L. major* was low and several other plant species were found. Some of them were locally abundant but none became dominant (personal communication J. Meeuse; Field observations and data Waterboard Hunze en Aa's; Appendix 1).

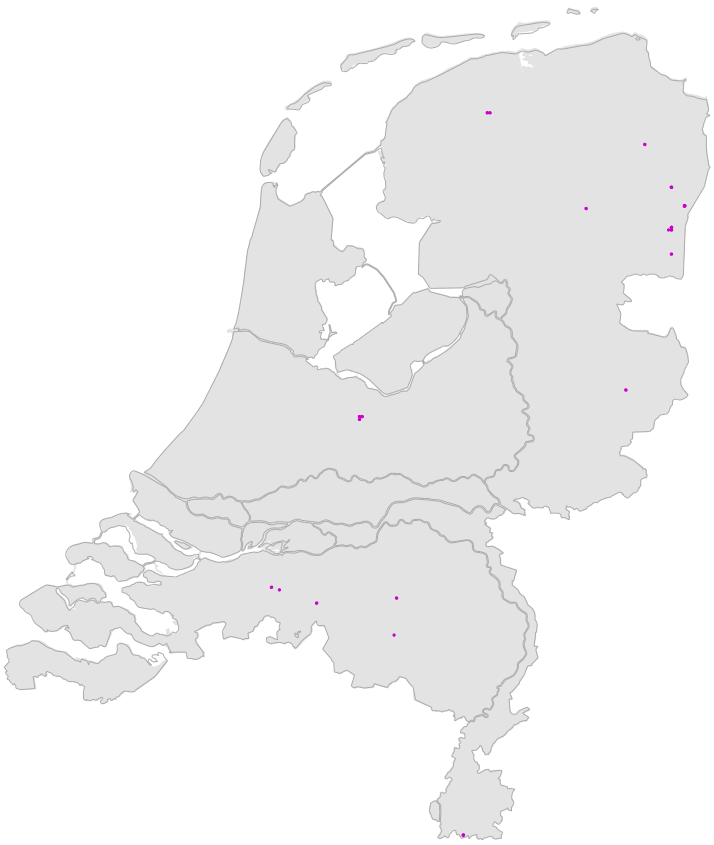

Figure 5.2: Distribution of Curly Waterweed (*Lagarosiphon major*) in the Netherlands since first introduction in 2003 (Data: National Database Flora en Fauna, complemented with data sources mentioned in section 2.2).

Figures 5.3 and 5.4 show trends in the yearly number of kilometre squares containing new records of *L. major*. These are based on non-systematic distribution data. The graphs indicate that *L. major* was first recorded in the Netherlands in 2003 when it occupied 4 kilometre squares. However, the plants were located a single location around the junction of four kilometre squares. The rate of dispersal peaked in the years 2007 and 2008. Since 2008 the number of reported records has decreased compared with preceding years. This, however, may well be an artefact as people no longer report the species for a particular site once it has been reported in preceding years. Moreover, a particular kilometre square may only be surveyed once every 5 years.

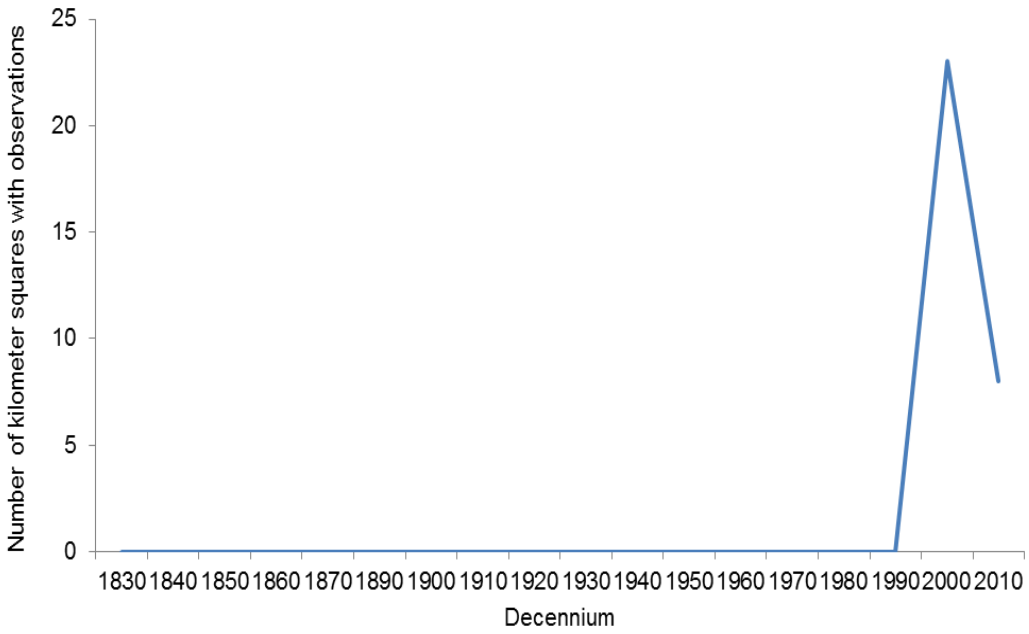

Figure 5.3: The number of km squares in the Netherlands where Curly Waterweed (*Lagarosiphon major*) has been observed.

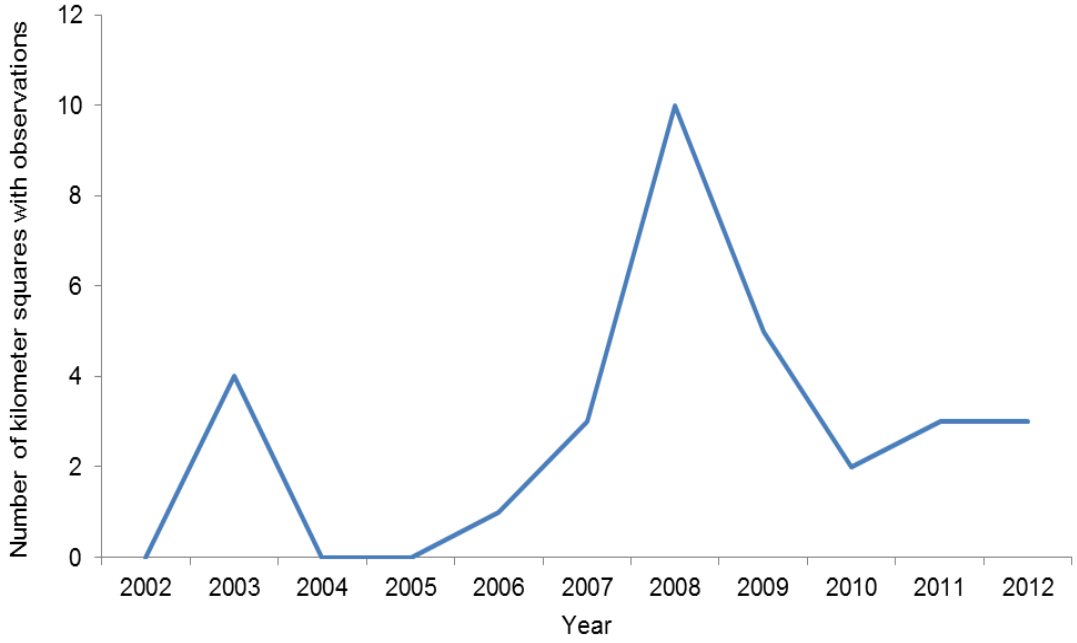

Figure 5.4: The number of km squares in the Netherlands where Curly Waterweed (*Lagarosiphon major*) has been recorded since 2002.

5.2.2. Colonisation of high conservation value habitats

To date, *L. major* is mostly confined to waters in and around urban areas. A potential high conservation value habitat in which *L. major* may appear is the EU Habitats Directive type H3150 (Natural eutrophic lakes with Magnopotamion or Hydrocharition-type vegetation). This habitat type features species like *Stratiotes aloides*, *Utricularia vulgaris* and *Hydrocharis morsus-ranae*.

5.3. Pathways and vectors for dispersal

5.3.1. Dispersal potential by natural means

Outside its South African native range, only female plants are known (Cook, 1982; National Botanic Gardens, 2007) and all reproduction is by fragmentation or vegetative reproduction. Neither the male flower, which floats freely to the surface, nor fruit or seeds have been recorded outside of its native range. Reproduction and dispersal are facilitated by the detachment of small fragments and lateral branches that subsequently become rooted (Centre for Ecology and Hydrology, 2004).

5.3.2. Dispersal potential with human assistance

The introduction of non-native aquatic macrophytes into a country has almost certainly been via the trade in live aquarium plants, legal or otherwise (Bowmer *et al.,* 1995). In the United Kingdom experts undertaking a risk assessment of *L. major* believed that the plant entered all non-native areas by being sold as an aquarium plant in trade (GB Non-Native Species Secretariat, 2011). Brunel (2009) undertook a survey examining the importation of non-native aquatic plants to 10 countries in Europe. The Netherlands imported circa 5 million units of aquatic plants in 2006 and was the largest importer, coming top of a list of countries constituting of France, the Czech Republic, Germany, Hungary, Switzerland, Austria, Latvia, Turkey and Estonia. In 2006, some 20.000 units of *L. major* were imported to the Netherlands. These were used in aquaculture and garden ponds. The next most prolific importer of *L. major* was Germany where there were 5,200 records of import, however, this data was obtained over only 10 months in 2007 (Brunel, 2009). The increase in e-commerce has exacerbated the problem of invasive plant sale giving retailers the ability to advertise online and send plants in the post (Kay & Hoyle, 2001). E-commerce has allowed importers direct access to customers, increasing access to plants sourced from other countries. Once bought, there is a risk that unwanted plants may be disposed of in the freshwater system. The results of a recent survey examining the behaviour of consumers of aquatic plants in the Netherlands showed that 2% of the 230 respondents had disposed of aquatic plants in open water (Verbrugge *et al.,* 2011). Moreover, further proof of voluntary introductions is provided by the occasional occurrence of common garden pond plants and animals in Dutch waters with examples of pumpkinseed sunfish (*Lepomis gibbosus*). This fish species was introduced to the Netherlands in 1902 as an aquarium and garden pond fish (Van Kleef *et al.,* 2008). This disposal of aquatic plants in open water potentially contributes to the introduction and spread of invasive aquatic plants.

The potential for introduction of a species repeatedly and on a large scale into a new area is one of the most important factors that lead to invasiveness (Randall & Marinelli, 1996; Riis *et al.,* 2010). Therefore, the high level of imports, recent increase in e-commerce and consumer behaviour increase the likelihood that invasive species such as *L. major* will establish or increase their distribution in the Dutch freshwater network.

A search of Google.nl, while not representative of the total current availability of *L. major* in the Netherlands, revealed a number of examples where *L. major* was advertised for sale on plant retailers websites (Figure 5.5). The results showed that the search term

used had a large influence on the results found. Results obtained from *L. major* and Verspreidbladige waterpest contained no commercial websites and were heavily biased towards websites with information on the invasive nature of *L. major*. However, results obtained using the search term Gekroesde waterpest were biased towards retail and hobbyist websites. The results indicate that legislation and education of retailers and hobbyists must involve the use of all common names for *L. major* to avoid plants being sold under a name not used to educate retailers and the public. Also, the monitoring of retailers must involve the use of all commons names to avoid plants being missed.

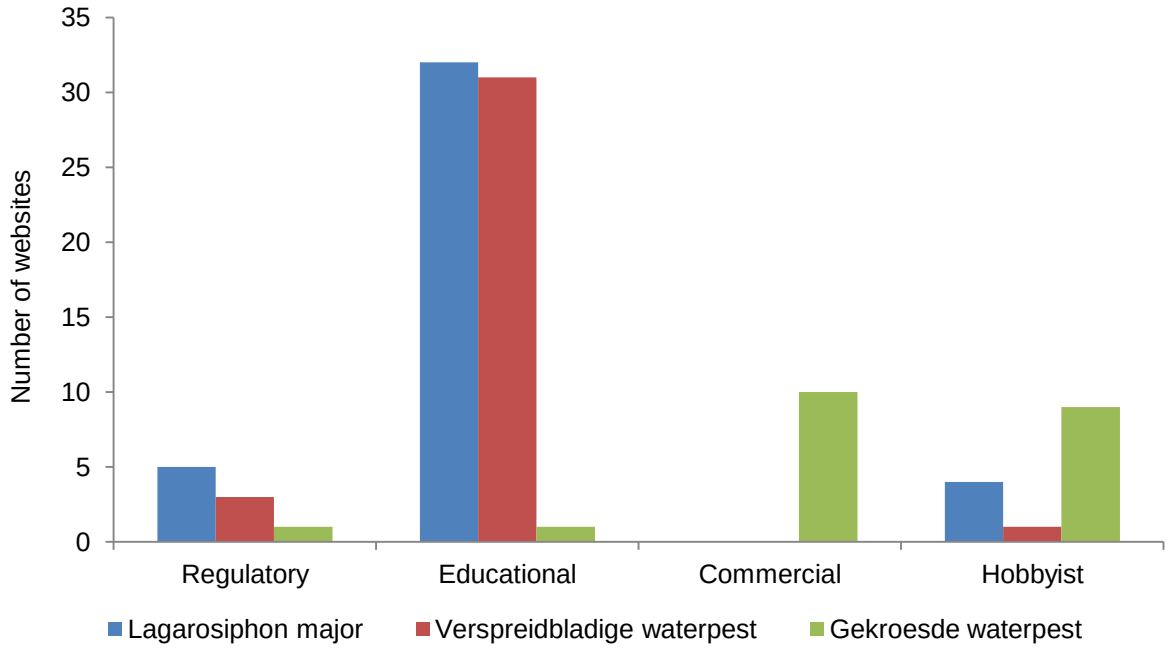

Figure 5.5: Type of websites featuring Curly Waterweed (*Lagarosiphon major*) found via Google.nl using various search terms (search terms are visualised by different colours).

As all reproduction of *L. major* occurs through fragmentation or vegatively, potential vectors that transfer plant fragments are of great importance (Table 5.1). Vegetative fragments are transferred between water bodies by boats and trailers, fishing, vehicles crossing fords, weed harvesters and other maintenance equipment; though rarely, if at all, by birds (Bowmer *et al.,* 1995; Johnstone *et al.,* 1985; Howard-Williams, 1993). Compton *et al.* (2012) linked the distribution of *L. major* in New Zealand lakes with human transport vectors. In this study high risk lakes lay in the vicinity of high human population densities, where lake access was relatively easy. Clayton *et al.* (1981) observed that *L. major* distribution was associated with the most occupied, developed, and recreationally used area of Lake Rotoma, New Zealand. The second most established area of *L. major* was at the opposite end of the lake, near the only other point of public access. The authors concluded that *L. major* appeared to have been accidentally introduced into Lake Rotoma on boats transported from infected lakes (Clayton *et al.,* 1981).

Establishment of vegetative fragments was often associated with fallen, submerged trees that have probably entangled drifting shoots and provided a point of anchorage from where establishment and further growth could occur (Clayton *et al.,* 1981).

Table 5.1: Potential dispersal vectors of Curly Waterweed (*Lagarosiphon major*).

Vector / mechanism	Mode of transport	Examples and relevant information	References
Water current	Downstream	Plant fragments transported in flowing water	Bowmer *et al.* (1995)
Hobbyists	Overland	Disposal of unwanted plants	Bowmer *et al.* (1995)
Trade	Overland (cross border)	E-commerce, plants transported in the post	Bowmer *et al.* (1995); Brunel (2009); GB Non-Native Species Secretariat (2011)
Boats / trailers	Upstream / downstream, overland	Occurs as a result of improper disinfection and moved from water body to water body	Bowmer *et al.* (1995); McGregor & Gourley (2002)
Fishing equipment	Upstream / downstream, overland	Occurs as a result of improper disinfection and moved from water body to water body	McGregor & Gourley (2002)
Vehicles	Upstream / downstream, overland	Plants become trapped when crossing fords and subsequently transported	Bowmer *et al.* (1995)
Weed harvesters	Upstream / downstream, overland	Machinery not properly disinfected move from water body to water body	McGregor & Gourley (2002)
Large aquatic birds	Upstream / downstream, overland	Rare occurrence	McGregor & Gourley (2002); GB Non-Native Species Secretariat (2011)

5.4. Invasiveness

Since it was first recorded in the Netherlands in 2003, dispersal has progressed slowly. By 2012, 31 kilometre squares had been recorded that contained *L. major* (Figure 5.4). The distribution of *L. major* within the Netherlands is characterised mainly by a number of records that are distant and isolated from each other suggesting that records originate from mainly isolated introductions (Figure 5.2). Spread has been limited away from and around urban areas where all introductions have occurred. Reasons for the limited dispersal after initial introduction maybe most colonised sites are located in isolated water bodies , show low water velocity or a lack of dispersal vectors. However, there are a few examples where locations are remotely interconnected by rivers and canals, such as in Drenthe and Groningen. In the water course near Ter Apel *L. major* was removed in 2008. At this location downstream colonisation of plant fragments was not recorded. Therefore, it appears that *L. major* has displayed a low capacity for invasiveness within the context of the Netherlands.

6. Impacts

6.1. Ecological effects

6.1.1 Impacts on native species

Adverse effects

The major adverse impacts of Curly Waterweed *(Lagarosiphon major)* are related to interference and exploitation competition. In the heavily colonised Lough Corrib, Ireland the impact on native and other non-native species has been dramatic. Assuming that the surrounding lakes of Lough Corrib feature a similar species composition to that that existed in Lough Corrib prior to *L. major* invasion, characteristic dense meadows of charophyte vegetation, mixed with tall stands of *Myriophyllum spicatum, Elodea canadensis* and a range of *Potamogeton* species have been lost (Caffrey & Acavedo, 2007). These impacts have also been observed in other locations where *L. major* has invaded. Following the invasion of Lake Taupo in New Zealand, the number of native species decreased markedly, the most noticeable decrease occurring at 4 m depth. Moreover, large weed beds of *L. major* attracted herbivorous birds and detritivores such as swans and crayfish which also adversely affect the native flora (Howard-Williams & Davies, 1988). The replacement of an established invasive weed, by another from the same family has previously been thought to be of little consequence. However, in New Zealand, *L. major* was able to grow taller and denser than *E. canadensis*, with the result that biodiversity was further reduced and surface-reaching weed beds posed even greater interference to water body usage (Champion & Clayton, 2000). In other locations, however, *L. major* has proven to be less aggressive. In some areas of New Zealand *L. major* has been displaced by other species and may co-exist with native species (McGregor & Gourley, 2002).

Research has demonstrated the competitive ability of *L. major* fragments over those produced by other tall aquatic plant species (Rattray *et al.,* 1994). Shoot fragments possess the ability to absorb nutrients from the water as well as using stored nutrients. Where nutrients are plentiful in the water, *L. major* channels its growth resources into shoot extension rather than into root development. This is particularly advantageous in aquatic situations where light may be limiting. However, nutrient availability was not found to be an important factor in the replacement of *Elodea nuttallii* by *L. major* observed in British inland waters, suggesting that other factors apart from nutrient status determine replacement (James *et al.,* 2006).

L. major demonstrates a competitive advantage over other macrophytes in the way it uses bicarbonate. For example, *L. major* seems competitively superior to *Elodea spp*. when grown together in tanks simulating lake conditions (James *et al.,* 1999). *L. major* is able to maintain higher photosynthetic rates than *Elodea* spp., even with a decrease in free CO_2, due to a more efficient bicarbonate utilization (Cavali *et al.,* 2012). Efficient bicarbonate utilization is the key to *L. major's* success in dominating mixed plant communities as prolonged periods of high pH will suppress the photosynthetic performance of less aggressive submerged macrophytes (Stiers *et al.,* 2011). Moreover, *L. major* has higher photosynthetic rates and bicarbonate use efficiency than two other potentially invasive aquatic plant species, Hornwort (*Ceratophyllum demersum*) and the

Large-flowered Waterweed (*Egeria densa*), when grown at low alkalinity, possibly indicating a competitive advantage under these conditions. Research has shown that photosynthesis can elevate pH to values over 10 in small ponds (Centre for Ecology and Hydrology, 2004). This contributes to the success of the plant in mixed communities, as few submerged macrophytes can photosynthesise effectively in such high pH environments (Caffrey & Acavedo, 2007).

In the Netherlands, during winter, plants stop growing and sink to the bottom to avoid colder surface water temperatures and avoid damage. This effect has also been observed in northern Britain (Centre for Ecology and Hydrology, 2004). In very shallow water (maximum 30 cm) where freezing may occur during Dutch winters, plants may suffer damage as they cannot sink away from the surface. The time of year at which plant growth is triggered will differ per location dependent on temperature. In other more southerly locations, where the climate is warmer, growth will occur all year round (R. Pot, unpublished observations).

Experimentation exploring the impact of climate warming on the growth of *L. major*, *Elodea nuttallii* and *Potamogeton natans* demonstrated that *L. major* was the only species that favoured an increase in water temperature. Experiments consisted of a two year simulation where water temperatures were raised to a constant 3 ^{o}C over ambient conditions. Results demonstrated an increase in growth rate and in the proportion of each community made up by *L. major* (McKee *et al.*, 2002). This has important implications as future climate change may increase the competitive ability of *L. major* over indigenous species.

De Carvalho *et al.* (2007) investigated the uptake of pesticides in *L. major* and Floating Duckweed (*Lemna minor*). They concluded that aquatic plants may be an appreciable sink for pesticide contaminants in water, especially for the more lipophilic compounds, which together with metabolism of these compounds within the plant tissues will facilitate removal of pesticides from contaminated waters. Submerged plant species showed higher Chromium accumulation than do floating and emergent ones. *L. major* has also been show to accumulate Chromium at higher levels than either Curled Pondweed (*Potamogeton crispes*), Water Chestnut (*Trapa natans*) or Reed (*Phragmitis communis*) (Chandra & Kulshreshtha, 2004). Arsenic has also been shown to bioaccumulate in aquatic plants and was shown to accumulate to a level of 300 mg/kg in 1983 in a lake treated with high levels of the pesticide Sodium Arsenite in 1959. However, other aquatic plants accumulated Arsenic to a higher level (the green algae, *Chara corallina* and *Nitella hookeri* accumulated to a level of 340 and 1200 mg kg^{-1} respectively). Fish sampled in the study were found not to have bio-accumulated Arsenic and contained values below the permissible level for human consumption in New Zealand (Tanner & Clayton, 1990; Department of Primary Industries, 2011).

The result of the literature search revealed no information relating to the transmission of parasites and diseases. Impact criteria related genetic effects are not relevant for the Netherlands. Hybridisation or introgression with natives will not occur because closely related species are absent.

Positive effects
No direct positive effects on native species were found during the literature search.

6.1.2. Alterations to ecosystem functioning

Adverse effects

Low light levels and the deep, often anoxic mud deposits that exist beneath the *L. major* canopy make it very difficult for other aquatic plant species to exist (Caffrey & Acavedo, 2007). One of the main physical habitat modification is due to the canopy formed by *L. major*. Where mature surface-reaching stands have become established, the canopy is able to shade out, and competitively exclude, even tall submerged species (Figure 6.1). It has been demonstrated that as little as 1% sunlight can penetrate a canopy of 0.5 m deep (Schwarz & Howard-Williams, 1993). The presence of dense stands of macrophytes can have a number of other effects including changes in nutrient availability and resource pools. *L. major* presence increases dissolved reactive phosphorous and dissolved inorganic nitrogen and results in changes in temperature and dissolved oxygen level (Schwarz & Howard-Williams, 1993; Department of Primary Industries, 2011).

Figure 6.1: Dense vegetation of Curly Waterweed (*Lagarosiphon major*) in a ditch near Ter Apel, the Netherlands (Photo: R. Pot).

The presence of invasive aquatic plant species impacts on fish populations. Heavy infestations confer no oxygen benefit on fish and other animals (Ramey, 2001). Food webs involving fish species may be effected directly due to the change of species food source availability following *L. major* invasion. In an experiment examining the food preferences of the Grass carp (*Ctenopharyngodon idella*), *L. major* was found to be least palatable compared to a group of 9 other species of waterweed, which is generally in agreement with previous results on weed preferences (Edwards, 1974). Changes in fish populations have wider economic and recreational consequences. Colonisation of Lough Corrib in the west of Ireland by *L. major* has led to changes in the survival and composition of fish species that could have major impacts on the Brown Trout and Salmon fishery (Caffrey, 2009).

Significant changes in abundance and species composition within the macroinvertebrate community have been observed following invasion by *L. major*. Particular differences

have been noted in the abundance of sedentary taxa, including Chironomidae and Mollusca. The most notable difference, however, reflected the significant increase in the abundance of certain macroinvertebrate groups e.g. Chironomidae (Caffrey & Acavedo, 2007). This observation has been repeated in other studies. In Lake Wanaka, a large alpine New Zealand lake, *L. major* and *E. canadensis* contributed to greater standing stocks and productivity of epiphyton. Invertebrate communities were less dense (1890/m^2 vs 4030/m^2) and less diverse (richness = 9 vs 12). Invertebrate communities in native beds were dominated by snails, oligochaetes, and nematodes, whereas chironomids, snails, and caddisflies were dominant in non-native beds (Kelly & Hawes, 2005). However, other literature evidence contradicts these observations. Biggs and Malthus (1982) conducted research into the preference of macroinvertebrate groups for native and non-native macrophytes. There appeared to be no preference by the invertebrate fauna (in terms of either numbers of taxa, abundance, or biomass) for either native plants or the non-native *L. major* as a habitat.

Positive effects

L. major has been associated with the Common bully (*Gobiomorphus cotidianus*), a goby species native to New Zealand (Kelly & Hawes, 2005; Bickel & Closs, 2008). Diet analysis indicated that Common bullies in the *L. major* dominated littoral zone of Lake Dunstan, New Zealand, fed on invertebrates (Mollusca, Trichoptera, Chironomidae) found on *L. major*, therefore suggesting its role as a food provider and effects on the foodweb in this system (Bickel & Closs, 2008). It is probable that structural changes of the habitat produced in mature *L. major* stands will better suit cyprinid, perch and pike populations than it will salmonid species. Salmonids have a preference for open water conditions while the cyprinids, perch and pike commonly seek the cover provided by dense weed beds (Caffrey & Acavedo, 2007).

In general, the height and complexity of the plant canopy in beds of non-native species results in a physical change in habitat that appears to provide more habitat for zoobenthic prey, more resting area for benthic fish such as bullies, and greater refuge from top predators than in native beds (Gilinsky 1984, Keast 1984, Gotceitas 1990, Schriver *et al.*, 1995, Valley & Bremigan 2002). *L. major* and other non-native species maybe the only aquatic plants that can tolerate the conditions and removal of these plants would further degrade the habitat (McGregor & Gourley, 2002).

Evidence relating to impacts on ecosystem functioning relating to changes in hydraulic regime, turbidity and modification to natural succession were not found during the literature search.

6.2. Socio-economic effects

In its native range (South Africa) as well as in introduced areas prolific growth of *L. major* can interfere with commercial navigation and water-based recreation (Centre for Ecology and Hydrology, 2004; Caffrey & Acavedo, 2007). Swimming maybe impossible in areas of dense weed growth (Figure 6.2) and the snarling of weeds in outboard motors may put recreational boaters at risk (Caffrey & Acavedo, 2007). Storms can tear the weed loose and deposit large masses of rotting vegetation on beaches, spoiling their amenity value; and effect power stations (Brown, 1975; Rowe and Hill, 1989). Water

velocity is slowed in dense beds of aquatic plants, particularly in those where there is a canopy and under-storey (Frodge *et al.*, 1990). Large beds of *L. major* may increase the risk of flow impedance as the discharge capacity of an invaded water body is reduced (Department of Primary Industries, 2011). Extensive growth can block the turbine screens of hydro-electric power stations in quantities too great for the cleaning machinery to clear, causing temporary shutdowns, economic losses and power shortages (Chapman *et al.*, 1974). Clayton & Champion (2006) stated that nearly all weed problems at power stations over the previous 30 years or more could be attributed to species that were not native to New Zealand, highlighting *L. major* as one of the most problematic weed species.

Figure 6.2: Diver emerges covered in Curly Waterweed (*Lagarosiphon major*) after swimming in infested lake (Aquatic Invasive Task Force, 2007).

In the United Kingdom the estimated yearly economic cost of *L. major* alone is 1,173,214 Pounds or approximately 1,466,400 Euros (Hulme, 2012). Controlling *L. major* by mechanical means was estimated to be 1,000 pounds or 1,250 Euros per hectare per year assuming that each 10 km square contains at least 1 hectare of plants (GB Non-Native Species Secretariat, 2011).

6.3. Public health effects

There was no information found concerning the public health effects of *L. major* during the literature study or in communications with project partners.

7. Available risk classifications

7.1 Formal risk assessments

Risk classifications are available for a number of European countries and Australia (Table 7.1). Formal risk assessment have been carried out in Belgium and Great Britain.

Table 7.1: Overview of risk classifications previously performed for Curly Waterweed (*Lagarosiphon major*).

	Belgium	**United Kingdom**	**Ireland**	**Spain**	**Australia (State Government Victoria)**
Scope	Ecological risk assessment	Risk assessment	Risk assessment	Weed risk assessment	Victorian Weed Risk Assessment
Method	ISEIA	DEFRA national risk assessment	IS Ireland Risk Assessment	WRA	WRA
Risk classification	**Black list**	**High risk**	**High risk (score 20)**	**18**	**Not available**
Source	http://ias.biodiversity.be/species/show/68	https://secure.fera.defra.gov.uk/nonnativespecies/index.cfm?sectionid=51	Irish Invasive Species Database (2007)	Andreu & Vila (2010)	http://vro.dpi.vic.gov.au/dpi/vro/vrosite.nsf/pages/impact_Lagarosiphon
Additional information	Recorded in 'consensus list' ALTERIAS. This means that an agreement has been made to stop the sale of plants. http://www.alterias.be/images/stories/downloads/Nederlands/consensuslijst_gedragscode.pdf	Additional rapid risk assessment undertaken: ranked as a critical species and recommended for more detailed risk assessment as a matter of priority by Natural England http://publications.naturalengland.org.uk/publication/40015?category=47020	Most Unwanted Species http://invasivespeciesireland.com/most-unwanted-species/established/freshwater/curly-waterweed		Species banned in New Zealand http://www.fnzas.org.nz/?cat=92

In Belgium, Curly Waterweed *(Lagarosiphon major)* scored a maximum of 12 out of a possible 12 using the ISEIA protocol and was assigned the highest possible risk category (http://ias.biodiversity.be/species/show/86; last accessed August 11, 2012). As a result, *L. major* was placed on a black list indicating species that pose a high environmental risk.

In the United Kingdom, Natural England carried out an assessment using a rapid screening process designed to be applicable to larger numbers of plants (Horizon scanning). *L. major* was ranked as a critical species and recommended for more detailed risk assessment as a matter of priority (Natural England, 2011). Application of the formal UK Risk Assessment Scheme resulted in *L. major* being given a high risk rating. In the UK assessment, high risk species are defined as those known or likely to have harmful consequences.

In Ireland *L. major* is defined as high risk, scoring 20 in the Invasive Species Ireland risk assessment (Anonymous, 2007). In Ireland the impacts of *L. major* are described as

resulting in significant changes to the ecology of the invaded habitat for native plants, insects and fish. This species is also listed as most unwanted species in Ireland.

7.2 Other risk classifications

In Spain, *L. major* scored 18 on a scale ranging from -14 to 30 on the Weed Risk Assessment protocol (WRA). According to Andreu & Vilà (2010) species with a WRA score over 6 should be rejected for introduction due to their potential impacts.

In Australia, the Victorian Weed Risk Assessment (WRA), while not giving an overall score for *L. major,* categorised *L. major* as high risk for adverse impacts to water quality and native plant species resulting from structural habitat change.

Finally, *L. major* is a banned species in New Zealand.

8. Management options

8.1. Prevention

Combating the introduction of invasive plant species involves a number of stages that should be applied in order. The first stage is to prevent the spread of the species crossing a countries border. The second stage is the prevention of release to the freshwater system from isolated locations such as aquaria or garden ponds, by accident or deliberately. The third stage is prevention of dispersal through connected waterways and overland via vectors from the site of introduction. The main distribution channel or vector is trade of plants for aquaria and garden pools. The best alternative native species is *Ceratophyllum demersum*. A potential alternative for Curly Waterweed *(Lagarosiphon major)* for trade is *Elodea nuttallii*. This is also a non-native species, but has established and has become very common. New introductions of *E. nuttallii* are expected to have no additional effects in the Netherlands. Public awareness is an important component in a strategy aimed at controlling or removing an invasive species from a catchment area. This is especially true of species such as *L. major* where people are a major vector of dispersal. Awareness leaflets, press releases, calendars, lakeside notifications and an information website, warning of the environmental, economic and social hazards posed by this plant will contribute to public awareness (Figure 8.1) (Caffrey & O'Callaghan, 2007).

Figure 8.1: Poster encouraging the reporting of sightings of Curly Waterweed (*Lagarosiphon major*) in Ireland (Caffrey & Acavedo, 2007; Photo reproduced with permission of J. Caffrey, Inland Fisheries Ireland).

Education of anglers and boaters may be especially useful as they can assist in reporting sightings of the plant. Moreover, instruction on the decontamination of boating and angling equipment is necessary to prevent dispersal of *L. major* facilitated by these vectors. Following the invasion of the ecologically important Lough Corrib in Ireland, a

guide to the identification of aquatic invasive species in Ireland was produced (Caffrey & O'Callaghan, 2007), which provided a simple photographic aid to the identification of a number of invasive species, including *L. major.* This guide warned of the problems associated with invasive species and describes how to avoid spreading them within the country. A similar field guide for the Netherlands, produced in conjunction with the 'Code of conduct on aquatic plants', was produced by Van Valkenburg (2011). Its aim is to create awareness and assist in the monitoring of non-native aquatic plants.

8.2. Eradication and control measures

8.2.1. Manual and mechanical control

Once widespread, control would be extremely difficult (as is the case for most submerged aquatics) (Csurhes & Edwards, 1998). Moreover, the removal of aquatic macrophytes from a lake system should be done under careful consideration. Removal of non-native macrophytes can lead to the proliferation of algae rather than re-colonisation by native macrophytes (Perrow *et al.,* 1997; Donabaum *et al.,* 1999). However a number of management strategies have been employed in an attempt to combat infestations.

Manual removal may be more effective at removing newly colonised or plants at low-density sites. Hand removal and / or suction dredging were applied dependent on size of infestation to manage *L. major* in Lake Wanaka, New Zealand. Here, 99% of weeds were removed at certain locations (Clayton, 2006) . However, it was demonstrated how easy it was to overlook *L. major* shoots and how quickly plants can grow after two months. Effectiveness of removal was hampered by growth on firm substrates or entanglement in driftwood, increasing the likelihood that some stem material would be left behind. To ensure effectiveness, an emphasis was placed on the importance of follow up surveys after 8 weeks and the re-working of sites 3-4 months following initial removal efforts (Clayton, 2006). Manual removal may be combined with large scale mechanical harvesting. Manual handpicking the remaining fragments of the target species may be very effective in attempts to eradicate pest species, at least locally, and prevent spread.

A number of trials have been undertaken applying mechanical control in the management of *L. major.* Areas that were cut by passive means with the use of a blunt V-blade, (Figure 8.2) towed behind a boat removed an estimated 95% of *L. major* in Lough Corrib, Ireland. 8% regrowth had occurred 9 months following the treatment, at least partly from the dispersal of fragments from locations outside the cut area (Caffrey & Acavedo, 2007). It is important to note that divers were also required to assess the effectiveness of the V-blade as only 75% of the original biomass was removed after the initial cut at some locations. More intensive cutting led to removal of 95% of the original biomass at these locations. It was also noted that a considerable volume of tough root material was protruding from or lying on the mud substrate following the cut. In addition, occasional large rafts of cut vegetation lay on the lake bed and did not immediately float to the surface, hampering removal and increasing the risk of later re-growth (Caffrey & Acavedo, 2007). Further disadvantages are that the collecting of plant biomass is only possible partially and therefore spread is stimulated (Wade, 1990; Wijnhoven & Niemeijer, 1995).

Figure 8.2: V-blade used to cut Curly Waterweed (*Lagarosiphon major*) in Rinerroon Bay, Ireland (Caffrey & Acavedo, 2007; Photo reproduced with permission of J. Caffrey, Inland Fisheries Ireland).

In a further study the effect of *L. major* removal by mechanical means on the wider lake ecosystem was examined. The effect of macrophyte removal had only a temporary effect on macrophyte areal cover (4 months). Nevertheless, mechanical removal increased light penetration significantly. However, a difference in epiphyton biomass was not detected. Invertebrate biomass increased in macrophyte stands four months after treatment and there was a shift in the invertebrate community composition. Mechanical control had no effect on invertebrate biodiversity. The higher invertebrate biomass did not translate into a higher fish density in the treated areas. The results of this study indicated that partial mechanical removal is a suitable option to control unwanted macrophyte stands (Bickel & Closs, 2009). Removal by this method may encourage the recovery of native macrophyte species. Active mechanical harvesting was applied to control *L. major* invasion of New Zealand hydro-lakes. Re-growth declined after three, six-monthly harvests allowing the establishment of low growing native *Nitella* spp. beds in a clear water lake (Howard-Williams *et al.,* 1996). However, mechanical methods may result in the breakup of plant stems resulting in the dispersal of plants to new areas (Bowmer *et al.*, 1995).

L. major tends to survive over-winter in southern areas of Britain. Further north, as well as in the Netherlands, the plant mass sinks, but never dies down completely, meaning that early season cutting should be deeper than normal, or should be delayed until the plant has started to grow in late April. The growth characteristics of *L. major* are very similar to that of *Elodea nuttallii*. In general, control measures can be the same for these species. Control of *Elodea nuttallii* by cutting boats and mowing baskets is routine on a large scale in the Netherlands.

Several other machine types are available for cutting and collecting the plant material, examples of these are as follows (Wade, 1990; Wijnhoven & Niemeijer, 1995):

- Active cutting boats. Boats with cutter bars coupled to hydraulic control of the depth and angle of the cutter bar in the water (Figure 8.3). Plants are cut more efficiently than with cutting boats using a V-blade. They have the same disadvantage concerning collecting plant biomass and spread.

- Harvesting boats. Small boats with a hydraulic controlled rack on the front that can collect floating plants and transport them to the banks. Collecting plant biomass is only possible partially and spread is not prevented completely. Larger boats that cut and collect in one action are much more efficient but expensive and not practical in small water bodies.

- Mowing basket. A steel bucket with cutter bar attached to a hydraulic arm of a tractor or excavator that can be lowered in drainage channels, small rivers and ponds, and cut and collect plant material very efficiently. Loss of plants is scarce and therefore the machine is very suitable to prevent spread of unwanted species.

Figure 8.3: A weed cutting boat with adjustable mowing gear used for aquatic weed control in the Netherlands (Photo: R. Pot).

8.2.2. Biological control

Management using herbicides, manual / mechanical removal and suction dredging have the disadvantages of being costly, ineffective long term control and potential environmental impacts (Tanner & Clayton, 1984; Haley, 2000). The potential for the biological control of *L. major* was explored by reviewing its natural enemies in its indigenous range of South Africa. Of the phytophagous species examined, at least three were identified that were expected to exhibit a preference for *L. major.* A leaf-mining fly, *Hydrellia* sp. (Ephydridae) and another yet unidentified fly was recorded mining the stem of *L. major*. Two leaf feeding and shoot boring weevils, cf. *Bagous* sp. (Curculionidae) were recorded damaging the shoot tips and stunting the growth of the stem (Baars *et al.*, 2010). The hydrilla leaf-mining fly, *(Hydrellia balciunasi*) and the hydrilla stem boring weevil (*Bagous hydrilla*) have previously been released in the USA for the control of

Hydrilla (Bowmer *et al.*, 1995). Unfortunately there was no further information in the literature regarding the further trialling of these species as potential biological agents. In South Africa sterile triploid Grass carp, *Ctenopharyngodon idella* (Val.) were introduced in an effort to control *Potamogeton pectinatus* and *L. major*. Within a period of one year, the mean wet mass standing crop of both weeds in the treated lake declined from an initial 193,11 g/m^2 in March 1990 to 33,89 g/m^2 in January 1991. No major changes were encountered in the water chemistry of the lake. Reduction in weed growths coincided with changes in the populations of weed and fish-eating birds frequenting the lake (Venter & Schoonbee, 1991; Schoonbee, 1991). Further experiments in New Zealand indicated that Grass carp ate *L. major* at seven times its growth rate (Chapman *et al.*, 1974). The consumption of *L. major* by Grass carp is dependent on the weight of individual fish. Only fish weighing above 500 g can be expected to consume large quantities of *L. major* (Edwards, 1974). However, Grass carp will eat *L. major* if they have no other choice and it is not one of their preferred foods. In an experiment examining the food preferences of the Grass carp (*Ctenopharyngodon idella*), *L. major* was found to be least palatable compared to a group of 9 other species of waterweed, which is generally in agreement with previous results on weed preferences (Edwards, 1974). Therefore, the presence of other macrophytes that are potentially more palatable will have an effect on the effectiveness of this management option. The Grass carp was introduced for the management of aquatic weed control in 1973 and is therefore already present in areas of the Netherlands. The Grass carp may be considered for biological control, however, further introductions should be treated with caution as it is a non-discriminate grazer and, if not confined, may spread and impact the wider ecosystem. In general the introduction of biological agents is a potential pest risk in itself and are only suitable after thorough testing.

8.2.3. Chemical control

Since the withdrawal of all herbicides for use in aquatic environments there is no appropriate chemical method of control for these plants in the Netherlands. Nevertheless, experiences in other countries are reported in this document.

L. major is susceptible to herbicides containing terbutryn or dichlobenil. The preferred method of control is application of dichlobenil in March or early April. Application of terbutryn will kill most submerged vegetation and so should only be used where *L. major* is the dominant species. Control after late June with herbicides is usually not successful, as the sudden decline in photosynthesis causes a severe drop in oxygen concentration which will kill fish (Centre for Ecology and Hydrology, 2004).

It was postulated that the ineffectiveness of herbicides against *L. major* in Ireland was due to the delivery of a non-toxic dose of dichlobenil to the roots of the *L. major* beds because granules of herbicide became trapped in the dense vegetation canopy (Caffrey & Acavedo, 2007). However, there may be another explanation for its ineffectiveness. Hofstra and Clayton (2001) assessed the effectiveness of the herbicides endothall, triclopyr and dichlobenil against *L. major* and their toxicity to other non-target species in greenhouse tests. Endothall was found to kill coontail, *L. major* and hydrilla and some species of *Myriophyllum* and *Potamogeton* but not egeria or species of *Chara* or *Nitella.* Only transient growth effects were observed in target plants treated with triclopyr and dichlobenil (Hofstra & Clayton, 2001). Management using diquat in Lake Wanaka, New

Zealand was ineffective over the long term. A year following a second application that totally eradicated *L. major* stands, strong recovery occurred (Clayton, 2006). Therefore, repeated treatments appear to be necessary for long term control. Moreover, authors state that consideration of public sensitivities (e.g. the proximity to water intakes and recreational activity) as well as constraints for achieving adequate contact time (e.g. water velocity, weed bed size, density and location) need to be considered to encourage effective results (Clayton, 2006; Getsinger *et al.*, 2008). Public sensitivities for the usage of herbicides may be reduced by the use of containment nets that limit its spread to the target area (Clayton, 2006).

8.3. Ecosystem based management

In Lough Corrib, Ireland, trials were conducted on the use of a biodegradable jute material to control *L. major*. Mats were placed over the vegetation at trial sites in 100 m strips and secured in place by divers. At most of the treated sites the growth of the species was effectively controlled. At one site, one small (< 1 m^2) intact *L. major* stand was present in a small fold at the edge of the mat. The effectiveness of the application of geotextile was dependent on whether weeds in the treated area were cut prior to textile placement. The cutting of weeds prior to application allowed easier fixing of the geotextile to the lake substrate and a resultant absence of weed growth in the treated area. Where no weed cutting occurred, at least 50% of the plot that did not receive a cut prior to geotextile placement supported healthy *L. major* following the treatment with geotextile (Caffrey & Acavedo, 2007). In a similar study, biodegradable jute material was used in place of geotextile (Caffrey *et al.*, 2010). Eight indigenous plant species (four charophytes and four angiosperms) were recorded growing through the loose-weave jute fabric. However, by the end of the study period, no *L. major* was recorded as doing so. The authors concluded that jute has the potential for broader application in the management of nuisance aquatic weeds and in the restoration of native flora extirpated by these non-native species (Caffrey *et al.*, 2010). In the Netherlands, the waterboard Hunze and Aa is currently involved in a trial to judge the effectiveness of the light occlusion method using jute in canal H next to Emmer-Erfscheidenveen (Figure 8.4). Here, three 185 m stretches colonised by *L. major* are subject to different management strategies. The first strategy being no treatment , the second option being standard practice with a weed-cutting bucket in autumn operated from the bank, and the third option being coverage of the south side of the canal with jute matting. The circumstances here are very different from the Irish study: a shallow, small water body with extremely turbid water. The matting was placed on top of the vegetation stretching widthways halfway into the canal. The fabric was fixed to the bank with wooden pegs and weighted down with sandbags. Matting was put in place in November 2010. During an initial survey in spring 2011, plants were observed not to have grown through the matting, but were still present at the edge, in the central section of the canal where the upper part of the stems had not been covered by fabric. In September 2011 the fabric was covered by sediment, and new shoots of *L. major* were firmly rooted on top of the fabric, however, no growth through the fabric was observed. The shoots in the central section of the canal, that had escaped coverage, continued to grow and reached the water surface. Re-growth on top of the fabric was the result of fragments originating from other canal sections. In June 2012 *L. major* shoots were observed rooting up to a depth of 80 cm (personal communication J.L.C.H. van Valkenburg).

High nutrient loading is thought to increase ecosystem invasibility (Davis *et al.*, 2000) and lend competitive advantage of invasive species relative to native species (Daehler, 2003). In pond ecosystems, sediment dredging has been shown to be a successful restoration measure in reducing internal nutrient load (Søndergaard *et al.*, 2000). Stiers *et al.* (2011) assessed the effectiveness of dredging as a measure in reducing *L. major* and *Ceratophyllum demersum*, a plant native to the Netherlands. *L. major* performed better than *C. demersum* after dredging. The species accumulated more total biomass and a higher weight relative growth rate both in monocultures and mixed cultures. The authors postulated that the sediment used to simulate the 'after dredging' conditions may have been more favourable for the initial anchoring and hence lead to a more successful growth of *L. major*. It was concluded that sediment dredging would not be a solution to reduce performance of invasive *L. major*. It should also be noted that the comparison made was between a free floating plant (*C. demersum*) and a rooting plant (*L. major*).

Figure 8.4: Trials examining the effectiveness of light occlusion as a management option against invasive macrophytes in the Netherlands (Photo: J.L.C.H. van Valkenburg).

Winter and summer drainage is effective in areas of low ecological value such as artificial channels and reservoirs. In Australia, control is aided by draining and exposure of sediments to high summer temperatures or winter frosts, but draining for sufficient time is not always feasible, especially in larger canals (Bowmer *et al.*, 1995). Moreover, efforts at controlling *L. major* in New Zealand hydro-lakes using partial short-term draw down proved effective at reducing the amount of waterweed handled at the power generating station during the subsequent growing season (Chapman, 1974; Coffey, 1975). Drainage should occur at least once a year and, if exposed plants are left undisturbed, a period of 14 days is required for satisfactory control. Success is dependent on climactic conditions experienced during the drawn down period. Mechanical tilling, to uncover the protected lower regions and roots of the plants, encourages more rapid drying.

9. Conclusions and recommendations

9.1. Conclusions

- Curly Waterweed (*Lagarosiphon major*) has dispersed to a number of countries outside of its native range and has been declared an invasive species in many of these countries.

- A number of foreign risk assessments have declared *L. major* as a 'high risk' species.

- The level of import of *L. major* to the Netherlands for use in aquaria and garden ponds has been shown to be in excess of that seen for other European countries and the plant is sold freely at garden centres.

- The information type accessible to the Dutch public via Google.nl can be divided into that relating to education, highlighting *L. major's* invasive potential, or e-commerce, depending on the search term used.

- Humans appear to be the main vector of dispersal of *L. major*. Examples of vectors found in literature are: boats, anglers, vehicles, weed harvesters and, rarely, large birds.

- The limited distribution of *L. major* in and around urban areas and evidence showing that a small proportion of hobbyists dispose of plants into the freshwater network, suggests that voluntary introductions by the public may be the major pathway through which *L. major* reaches the freshwater network in the Netherlands.

- Wider dispersal away from these isolated points of introduction appears to be limited suggesting that the dispersal potential and invasiveness of *L. major* may be limited within the Dutch context.

- The colonisation of high conservation habitats has, at the time of writing, not occurred within the Netherlands.

- The impacts of *L. major* on native species and ecosystems within the Netherlands is currently limited, in other countries impacts on native species and the local ecosystem have been considerable.

- Examples of impacts seen away from the Netherlands are: loss of native macrophytes, changes in macroinvertebrate and fish species composition and effects on ecosystem functioning such as changes in light penetration, nutrient cycling, pH and oxygen concentration.

9.2. Effective management options

- If active control of *L. major* is required, as in Emmer-Erfscheidenveen, the best method is removal using harvesting machinery e.g. mowing baskets or harvesting boats, and the prevention of fragment spread. The best method to prevent spread of the species seems to be as reticent as possible with management. The plants did not spread at Soest and Ter Apel where no management method was introduced, nor at any of the other known sites in the Netherlands. However, the plants spread to connected water-bodies after cutting at Emmer-Erfscheidenveen. It would seem that cutting encourages the loss of cut fragments to the water column which subsequently drift on currents and establish by vegetative reproduction at other locations.

- Once the plants have established, eradication is very difficult. The best option is to isolate the local populations and intervene as little as possible. At the very least a natural lowering of fitness and abundance may be expected, as was previously observed in Ter Apel, the Netherlands.

9.3. Recommendations for further research

- The reasons given for the limited distribution and dispersal capacity of *L. major* are based on expert knowledge of the few areas within the Netherlands currently inhabited by *L. major*. Further research is required to support this expert judgement and further explain the reasons behind the limited distribution and dispersal potential of *L. major* in the Netherlands.

- Further research is required to establish the physico-chemical characteristics of habitats where *L. major* has established itself in the Netherlands. This will increase the reliability of predictions assessing if *L. major* is likely to colonise habitat types displaying different characteristics in the future.

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Appendices

Appendix 1: Results of field surveys 2012.

	1	2	3	
Species	***Lagarosiphon major***	***Lagarosiphon major***	***Lagarosiphon major***	
Location	**Emmer-Erfscheidenveen**	**Musselkanaal**	**Ter Apel**	
Date of field search	**27-06-2012**	**27-06-2012**	**27-06-2012**	
Amersfoort coordinates	262.718-535.413	263.739-551.303	268.905-544.875	
Water depth (cm)	80-120	60-140	30	
Transparency (cm)	25	120	80	
pH	6.53	7.08	7.07	
Alkalinity (meq l^{-1})	1.153	1.744	1.346	
Width (m)	11	15	8	
Water flow	lentic / no flow	lentic / no flow	slow	
Water type	peat area	canal in peat area, before sluice	shallow restored stream, behind fish ladder	
Surface area covered (m^2)	?	10	200	
Number of individuals/shoots	>500	>25	>25	
Phenology	veg	veg	veg	
Code water sample	LW1	LW2	LW3	
Code sediment sample	LS1	LS2	LS3	
Code barcoding	24FW	24M3	240K	
Tansley survey				
Species (growth form)	Tansley score	Tansley score	Tansley score	Frequency
Lagarosiphon major **(s)**	o	o	o	3
Hydrochaeris morsus-ranae **(d)**	f	lf	o	3
Lemna minor **(d)**	r	r	lf	3
Glyceria maxima **(e)**	ld		lo	2
Sagittaria sagittifolia **(e)**	o	lf		2
Ceratophyllum demersum (**s)**	r	a		2
Spirodela polyrhiza **(d)**		r	r	2
Sagittaria sagittifolia **(d)**	o			1
Phalaris arundinacea **(e)**	la			1
Ranunculus sceleratus **(e)**	r			1
Utricularia vulgaris **(s)**	r			1
Stratiotes aloides **(d)**	r			1
Potamogeton natans **(d)**		f		1
Nuphar lutea **(d)**		f		1
Potamogeton crispus **(s)**		r		1
Lemna trisulca **(s)**		o		1
Sparganium erectum **(e)**		r		1
Elodea nuttallii **(s)**			r	1
Myosotis palustris **(e)**			f	1
Rorippa amphibia **(e)**			f	1
Mentha aquatica **(e)**			la	1
Sparganium emersum **(e)**			o	1
Myriophyllum heterophyllum **(s)**			o	1
Lysimachia thyrsiflora **(e)**			lo	1
Ranunculus lingua **(e)**			la	1
Remarks	Roots up to 80 cm water depth and 2 m distance from bank	In standing water before sluices near banks; Sediment consisted mainly of terrestrial leaf litter		

Tansley/DAFOR score a: abundant; d: dominant; f: frequent; o: occasional; r: rare (note: prefix I was used for local); Growth form code d: floating; e: emergent; s: submerged.