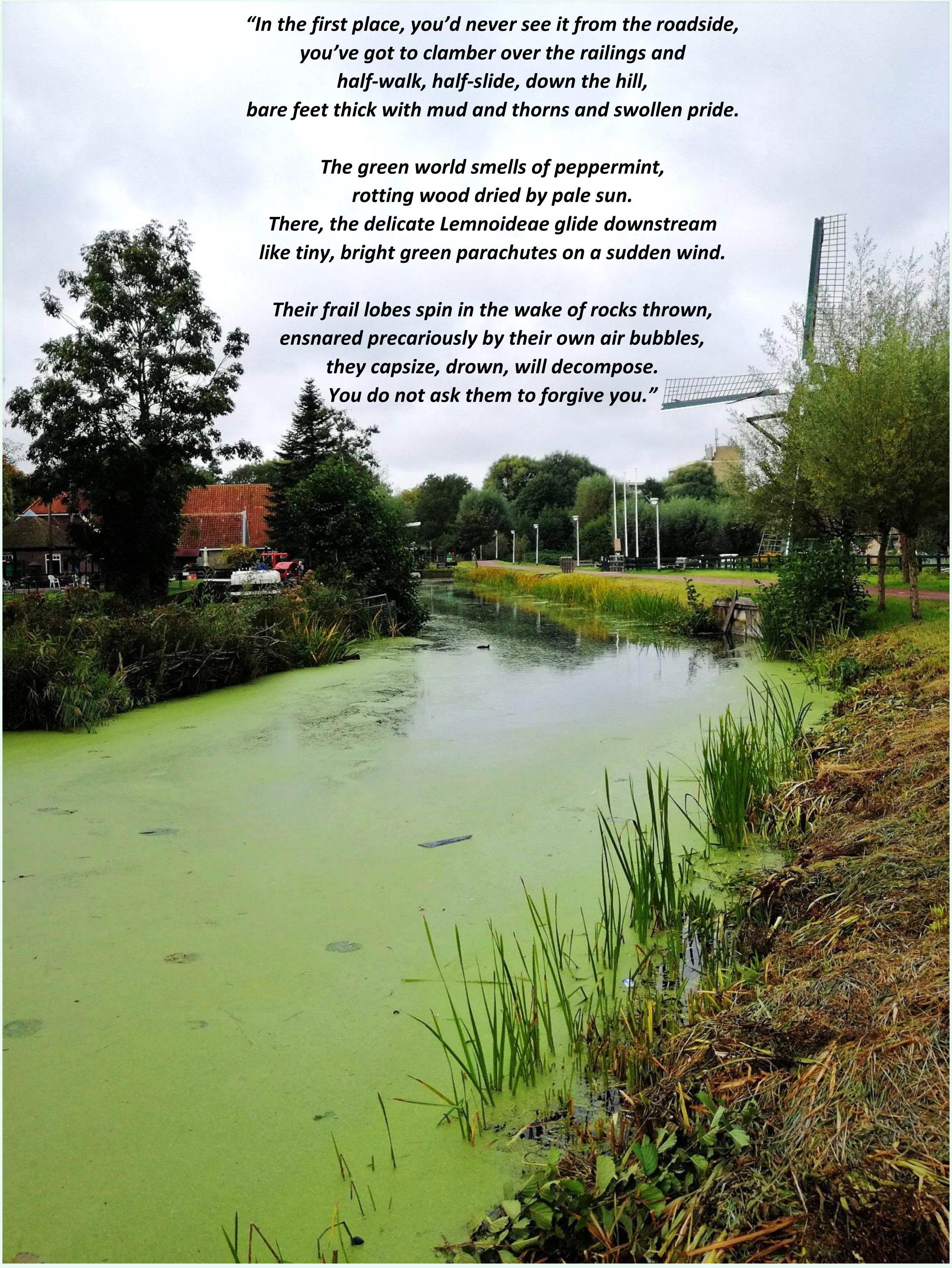
Duckweed in the High Ecological Value zones of Delfland

An investigation for the water board of Delfland into duckweed-related problem areas in the High Ecological Value network of Delfland, the Netherlands



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Abstract (EN)

Duckweed is a free-floating aquatic plant that grows in both still and running freshwater, such as lakes, rivers, and streams (Gupta & Prakash, 2013). Depending on the circumstances, duckweed can be an extremely proliferating species and can cause a decrease in ecological water quality in numeral ways (Sengupta et al., 2010)

This research has two main goals: the first goal is to gain insight in the correlations between duckweed coverage, several parameters of the natural environment and the ecological water quality. The second goal is to determine the magnitude of the decrease in ecological water quality caused by duckweed in (the HEV-network of) Delfland. The HEV-network is a coherent series of zones with aquatic plants that are fundamental in creating a habitat for macrofauna, fish and benthic algae (Hoogheemraadschap van Delfland, 2018).

This study is comprised of fieldwork activities, literature research and data analysis. During the fieldwork period, duckweed is monitored in six potential duckweed-related problem areas within the HEV-network: Kwekerijweg the Hague, Broeksloot Voorburg, Rodenrijseweg Berkel, Karikaatmolensloot Delft, Polderweg Schiedam and Delft city center. For each location, fourteen parameters are measured or estimated over the course of four weeks.

The correlations between five relevant driver parameters (nutrients, temperature, sludge depth, pH and movement by wind and current), duckweed coverage and four relevant state parameters (oxygen availability, (sun)light penetration, Electrical Conductivity and attractiveness) are calculated by executing multiple regression analyses. Literature is reviewed to compare the found correlations with relations found by others. Variance in duckweed coverage over time and space is researched by looking at satellite images, aerial photographs and infrared images. Found duckweed-related problem locations are combined with a map of the HEV-zones to analyze the severeness of the duckweed-related problems in those areas.

It is concluded from this research that duckweed is significantly correlated to the driver parameters nitrogen, phosphorus, temperature, pH and movement by wind and the state parameters oxygen availability and (sun)light penetration. the influence of duckweed on the ecological water quality in terms of macrophytes, macroinvertebrates and fish is negative but small. The values at which duckweed coverage has negative effects on the EWQ in terms of fish, macrophytes and macro invertebrates as formulated by the water board of Delfland seem to slightly overestimate the negative effects of duckweed on the EWQ.

Four out of eighteen or 22.2% of the water bodies in HEV-network of Delfland have an estimated degraded ecological water quality caused by duckweed coverage. As the six measurement areas are viewed as the worst-case scenarios of the HEV-network, it is assumed that the EWQ is not (severly) degraded by duckweed coverage in the rest of the HEV-network. From data collected in earlier studies, 3.72% of the measurement locations have an estimated degraded EWQ caused by duckweed coverage. Based on these values, it can be concluded that duckweed does not cause a problematic degradation in EWQ in most water bodies of Delfland. However, there are some locations that show to be problematic; Kwekerijweg the Hague, the city center of Delft, the Polderweg Schiedam and Leidschendam.

Samenvatting (NL)

Kroos is een vrij drijvende, aquatische plantensoort die kan groeien in zowel stilstaand als stromend zoet water, zoals meren, rivieren en beken (Gupta & Prakash, 2013). Afhankelijk van de omstandigheden kan kroos een extreem agressieve en overheersende soort zijn en een vermindering van de ecologische waterkwaliteit veroorzaken (Sengupta et al., 2010).

Dit onderzoek heeft twee hoofddoelen: het eerste is inzicht creëren in de verbanden tussen kroosbedekking, een aantal natuurlijke parameters en de ecologische waterkwaliteit. Het tweede is het beoordelen van de vermindering van de ecologische waterkwaliteit veroorzaakt door kroos in (het NEZ-netwerk van) Delfland. Het NEZ-netwerk is een netwerk van ecologisch belangrijke gebieden, waarin aquatische plantensoorten groeien die een fundamentele leefomgeving creëren voor macrofauna, vissen en algen (Hoogheemraadschap van Delfland, 2018).

Dit onderzoek bestaat uit veldwerk, literatuurstudie en data-analyse. Tijdens de veldwerk periode is kroosbedekking gemonitord in zes potentiële kroos-gerelateerde probleemgebieden binnen het NEZ-netwerk: Kwekerijweg den Haag, Broeksloot Voorburg, Rodenrijseweg Berkel, Karikaatmolensloot Delft, Polderweg Schiedam en het stadscentrum van Delft. Op elke locatie zijn veertien parameters gemeten of geschat over een periode van vier weken.

De verbanden tussen vijf relevante *driver parameters* (nutriënten, slibdikte, pH en beweging door wind en stroming), kroosbedekking en vier relevante *state parameters* (zuurstofconcentratie, (zon)licht penetratie, elektrische geleidbaarheid en aantrekkelijkheid) zijn berekend door middel van het uitvoeren van meervoudige regressieanalyses. Literatuur is bestudeerd om de gevonden verbanden te vergelijken met de verbanden die zijn gevonden in andere onderzoeken. Variatie in kroosbedekking in tijd en ruimte is onderzocht door het bestuderen van satellietfoto's, luchtfoto's en infraroodbeelden. Gevonden kroos gerelateerde probleemgebieden zijn vergeleken met een kaart van het NEZ-netwerk om de ernst van de kroosproblemen in deze gebieden te onderzoeken.

Uit dit onderzoek wordt geconcludeerd dat kroos significante verbanden heeft met de *driver parameters* stikstof, fosfor, temperatuur, pH en beweging door wind en met de *state parameters* zuurstofconcentratie en (zon)licht penetratie. Het verband tussen kroosbedekking en de ecologische waterkwaliteit is zeer complex en variabel maar kan worden aangenomen als licht negatief. De waarde die is geformuleerd door het Hoogheemraadschap van Delfland waarop kroos een negatieve invloed heeft op de ecologische waterkwaliteit op het gebied van macrofauna, macro invertebraten en vissen lijkt de werkelijke waarde te overschatten.

Van de achttien meetlocaties in het NEZ-netwerk van Delfland hebben vier meetlocaties een geschatte vermindering van de ecologische waterkwaliteit veroorzaakt door kroosbedekking. Omdat deze achttien meetlocaties worden gezien als meest problematisch op het gebied van kroos, kan worden aangenomen dat de ecologische waterkwaliteit in overige locaties binnen het NEZ-netwerk niet (ernstig) verminderd is door kroosbedekking. Uit data van eerdere studies blijkt dat 3,72% van de meetlocaties een geschatte vermindering van de ecologische waterkwaliteit veroorzaakt door kroosbedekking hebben. Gebaseerd op deze waarde kan worden geconcludeerd dat kroos geen ernstige vermindering van de ecologische waterkwaliteit veroorzaakt in de meeste wateren in Delfland. Echter, een aantal locaties zijn problematisch gebleken: Kwekerijweg den Haag, het stadscentrum van Delft, de Polderweg in Schiedam en Leidschendam.

Abbreviations

Abbreviation	Meaning
DPSIR	Driving forces–Pressure–State–Impact–Response. Functional analysis scheme associated with the European Environment Agency that helps to structure information (Ness et al., 2010).
EC	Electrical Conductivity. Measure of the ability of water to conduct an electrical current (Queensland Government, 2018).
EEA	European Environment Agency. The agency of the European Union which provides independent information on the environment (Nelson, 1999).
EWQ	Ecological Water Quality. An assessment of the quality of the structure and functioning of surface water ecosystems (EEA, 2018).
HEV-network	High Ecological Value network. Network of HEV-zones (High Ecological Value zones).
HEV-zone	High Ecological Value zone. Zone with aquatic plants that are fundamental in creating a habitat for macrofauna, fish and benthic algae (Hoogheemraadschap van Delfland, 2018).
KNMI	Koninklijk Nederlands Meteorologisch Instituut. Dutch national data- and knowledge center for weather, climate and seismology (KNMI, n.d.).
WFD	Water Framework Directive. European Union directive which commits European Union member states to achieve good qualitative and quantitative status of all water bodies (European Commission, 2012).

Species directory

Common name	Scientific name
Common duckweed	*Spirodela polyrhiza*
Common frogbit	*Hydrocharis morsus-ranae*
Gibbous duckweed	*Lemna gibba*
Hornwort	*Ceratophyllum demersum*
Least duckweed	*Lemna minuta*
Rootless duckweed	*Wolffia arrhiza*
Starwort	*Callitriche sp.*
Water fern	*Azolla filiculoides*
Western waterweed	*Elodea nuttallii*
White water lily	*Nymphaea alba*
Yellow water lily	*Nuphar lutea*

Contents

1. Introduction

1.1 Duckweed

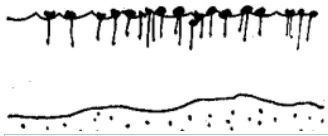

Figure 1: Systematic presentation of the growth strategy of duckweed. Source: Vymazal et al. (1998)

Duckweed is a free-floating aquatic plant (figure 1) that grows in both still and running freshwater, such as lakes, rivers, and streams (Gupta & Prakash, 2013). Depending on the circumstances, duckweed can be an extremely proliferating species or a welcome aquatic plant. Duckweeds belong to the family of *Lemnaceae* and have four genera: *Lemna*, *Spirodela*, *Wollfia*, and *Wolffiella* (Les et al., 2002). Some species develop root-like structures in open water which either stabilize the plant or assist it to obtain nutrients where these are in low concentrations. About 40 species are reported worldwide. The plant structure is relatively simple, devoid of distinct roots, stalks or leaves (Haustein et al., 1990). The plants usually have small vestigial roots and grow in the form of thick green carpets of rounded free-floating thalloids; flattened structures which resemble leaves. Duckweed can rapidly spread to cover a waterway resisting all attempts to eliminate it. These plants typically reproduce by budding, although they can produce small flowers on occasion, and prefer water which is rich in nitrogen and other nutrients (Groot et al., 1987). Duckweeds readily filter substances including toxins out of the water and can provide a habitat for new organisms, in the form of shelter for aquatic animals or nutrition for larger creatures like ducks and geese (STOWA, 2014). Voluminous literature is available on the usages of duckweeds for water quality improvement and nutrient removal (Al-Nozaily et al. 2000a, b; Cheng et al. 2002; El-Shafai et al. 2004).

Duckweeds are a rich source of proteins in the plant kingdom (Fasakin, 1999) and have a better array of essential amino acids that resembles animal protein than most plant proteins (Hillman and Culley, 1978). Furthermore, its amino acid spectrum is much higher as compared to other plants animals feed on (Rusoff et al., 1980; Mishra, 2007). The nutritive value of duckweeds is comparable to that of soybean. Some species of duckweed are considered attractive, making them potentially appealing as ornamentals in the garden. Some have even been genetically engineered to perform specific functions (Gijzen and Khondker, 1997). Also, duckweeds can be used in the process of wastewater treatment as a nutrient remover (Körner et al., 1998; Zhao et al., 2014).

Species of duckweed that are most common in the research area and will be distinguished in this research are: Gibbous duckweed (*Lemna gibba*), Least duckweed (*Lemna minuta*), Common duckweed (*Spirodela polyrhiza*) and Rootless duckweed (*Wolffia arrhiza*). These species are shown in figure 2. Another pleustophytic microfloral species that is taken into account in this research is Water fern (*Azolla filiculoides*). This species does not belong to the family of *Lemnaceae*; it is able to fixate nitrogen from the atmosphere and is therefore not dependent on nitrogen concentrations in the water body, whereas all other species of duckweed are (Hiscock, 2003; STOWA, 2014). However, it is hypothesized to have the same effects on ecology as duckweed, which is why it is taken into account in this research.

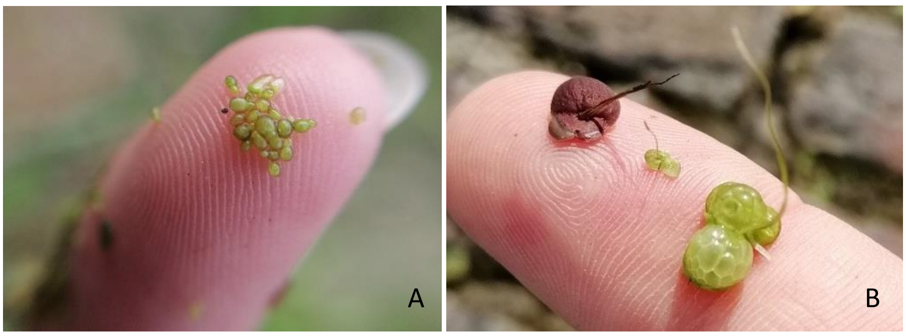

Figure 2A: Rootless duckweed (*Wolffia arrhiza*). Figure 2B: Common duckweed (*Spirodela polyrhiza*, left), Least duckweed (*Lemna minuta*, middle) and Gibbous duckweed (*Lemna gibba*, right).

1.2 Water board of Delfland

The area of Delfland is situated in the west of the Netherlands and is bordered by the North Sea, the Nieuwe Waterweg and the cities Berkel En Rodenrijs and Voorburg. The exact boundaries of the area are shown in figure 3 by the green line. The size of the area is 41,000 hectares and it inhabits nearly 1.4 million people. The water management in this area is executed by the water board of Delfland, which is founded in the year 1289.

One of the tasks of the water board of Delfland is to conserve and improve the ecological- and chemical quality of the surface water within the area. It follows the European Water Framework Directive (WFD), in which it is stated that the chemical and ecological quality of all waters should be sufficient by 2027 (Kallis & Butler, 2001). In the Netherlands, the biggest or most important water bodies are entitled WFD-waters and all other waters are disregarded; the chemical and ecological quality of all WFD-waters should be sufficient by 2027. To reach the ecological part of this goal, the water board of Delfland has set up a network of High Ecological Value zones (HEV-network).

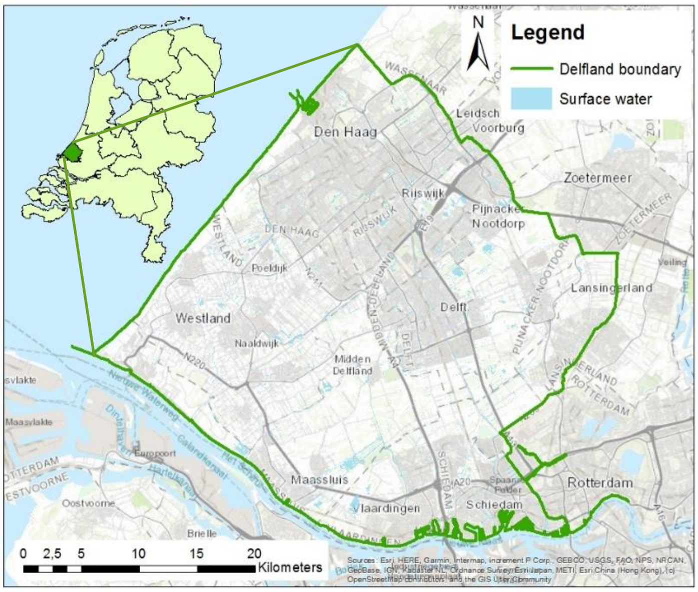

Figure 3: Area of Delfland.

The HEV-network is a coherent series of High Ecological Value zones (HEV-zones) within the WFD-waters; zones with aquatic plants that are fundamental in creating a habitat for macrofaunal, fish and benthic algae (Hoogheemraadschap van Delfland, 2018). The HEV-network consist of three types of HEV-zones: main zones, stepping stones and corridors. The main zones are areas in which a species is present in big enough numbers to make local extinction relatively unlikely. The stepping stones are smaller areas that function as a temporary habitat for species that migrate between the main zones. The corridors are relatively long, narrow areas that connect main zones and stepping stones. The HEV-network of Delfland is shown in figure 4, in which dark green circles represent main zones, light green circles represent stepping stones and light green arrows represent corridors.

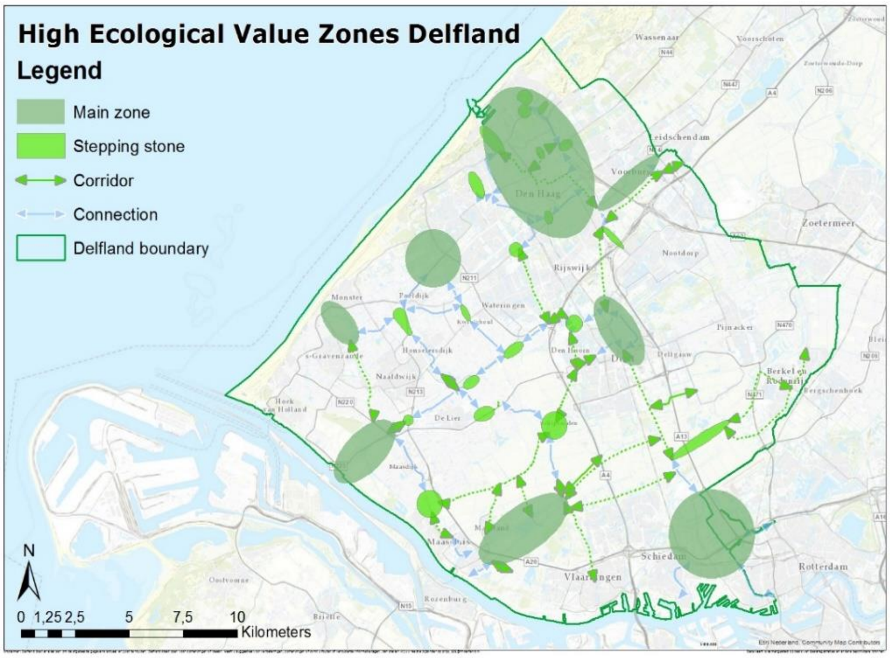

Figure 4: Network of High Ecological Value zones in Delfland.

1.3 Duckweed in Delfland

Apart from the positive effects or uses of duckweed described in paragraph 1.1, it has been shown that the existence of duckweed in the natural environment can cause a decrease in *ecological water quality* (an assessment of the quality of the structure and functioning of surface water ecosystems, from here on further referred to as EWQ) in numeral ways (Sengupta et al., 2010). For example, duckweed can cause oxygen rates to decrease and with thick masses of duckweed, light can no longer penetrate the water body. This causes other aquatic species to wilt or flee and decreases the biodiversity. However, the exact quantitative effects of duckweed on ecological quality are still debated. Yet the theoretical and visible effects are alarming enough for water boards to start making changes beneficial to reducing or eliminating the growth of duckweed. In the meantime, waterboards are working hard to produce empirical evidence for the ecological damage caused by duckweed.

Until 2014, most water boards took passive action towards duckweed; cleaning it when there are complaints from residents (STOWA, 2014) or when ecological goals of the WFD are exceeded (Peeters et al., 2013). Recently some water boards are in transition to execute active action towards duckweed. One of those water boards is the water board of Delfland. In order to protect other aquatic species and preserve the biodiversity, the water board of Delfland aims to investigate whether reducing the amount of duckweed on their surface waters, especially in the HEV-zones, is beneficial for the ecologic water quality.

To gain insight in the cause-effect relationship of duckweed on ecological quality, the DPSIR framework is used. DPSIR stands for Driving forces–Pressure–State–Impact–Response (Ness et al., 2010). The DPSIR framework is a functional analysis scheme associated with the European Environment Agency (EEA) that helps to structure information. It makes it possible to identify important relations as well as to develop an overview and understanding of a problem (EEA, 1999, Bowen and Riley, 2003, Giupponi, 2002, Giupponi, 2007). The DPSIR framework that is created for this research is shown in figure 5. The Responses in this framework are the defined societal (decision-making) measures to correct the problems of the previous phases. As a societal feedback, responses can be directed toward any of the first four stages. They often take the form of policy and/or planning actions. Responses can be either adaptive or mitigative (Bowen and Riley, 2003; EEA Report, 1999; Ness et al., 2010). Other studies have been executed to define the most effective response measures (e.g. Elshof, 2016; Raaphorst, 2015). In this research, the responses are not included.

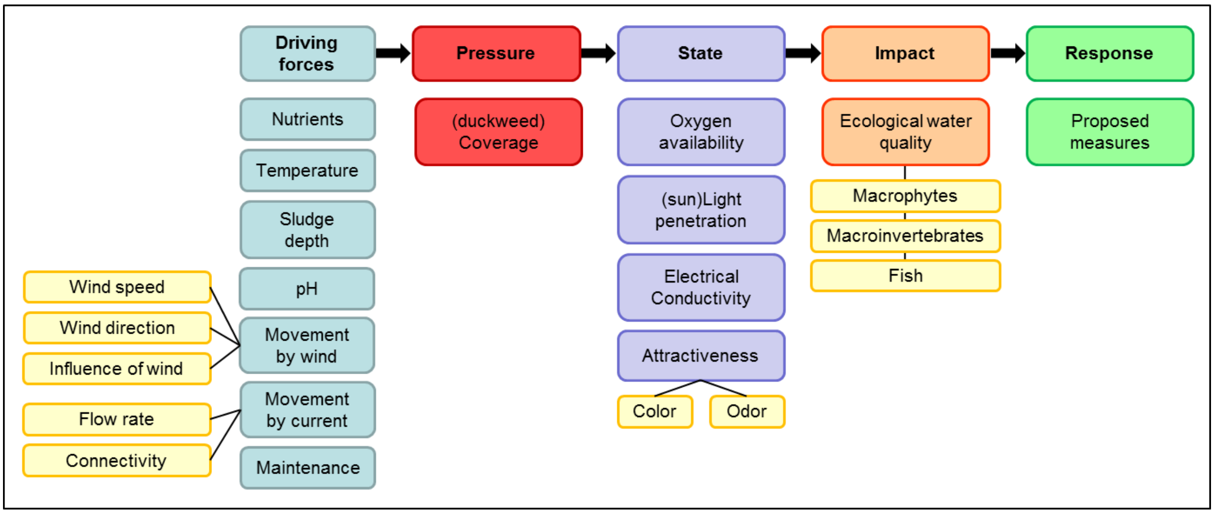

Figure 5: Schematic framework of relevant parameters

The amount of duckweed present in Delfland fluctuates per day and per location. For this reason, the water board of Delfland wants to gain more insight on which water bodies in Delfland are sensitive to the growth of duckweed and which water bodies experience negative effects of duckweed on the EWQ. This research has two main goals: the first goal is to gain insight in the correlations between duckweed coverage, several parameters of the natural environment and the EWQ. The second goal is to determine the magnitude of the decrease in EWQ caused by duckweed in (the HEV-network of) Delfland. To achieve these goals, the following research question and sub questions are deducted:

To what extent does duckweed cause a decrease in ecological water quality in (the HEV-network of) Delfland?

1) How do duckweed and environmental parameters influence each other and the ecological water quality?
    a) How are the driver parameters (nutrient availability, temperature, sludge depth, pH and movement) correlated to duckweed coverage?
    b) How is duckweed coverage correlated to the state parameters (oxygen availability, (sun)light penetration, EC and attractiveness) and how does this affect the ecological water quality?
2) Is duckweed causing degraded ecological water quality in (the HEV-network of) Delfland?
    a) What is the current state* of duckweed coverage in six potential problem areas in the HEV-network of Delfland (Kwekerijweg the Hague, Broeksloot Voorburg, Rodenrijseweg Berkel, Karikaatmolensloot, Delft city center and Polderweg Schiedam)?
    b) How did the duckweed coverage in these areas fluctuate over time and what does that say about the ecological water quality?
    c) Is duckweed causing degraded ecological water quality in other potential problem areas in Delfland that should be investigated?

The methods to answer these questions are explained in the next chapter. Sub questions 1a and 1b will be discussed in chapter 3, paragraph 3.1 and 3.2 respectively. Sub question 2a, 2b and 2c are discussed in chapter 4; respectively in paragraph 4.1, 4.2 and 4.3.

* Fieldwork activities are executed in September and October of 2019. From here on further in this research, the 'current state' represents the state during this fieldwork period. The state is not fixed and might have changed during the research and the process of writing this report. Therefore, the current state depicted in this research cannot be trusted to still be relevant at the time this report is received.

2. Methods

This study is comprised of fieldwork activities, literature research and data analysis. Scientific articles, books or other scientific publications will be consulted using the (online) library of the Vrije Universiteit Amsterdam, the shared data portal of the water board of Delfland and open sources on the world-wide web. Datasets and maps based on earlier studies by the water board of Delfland are used for comparison and completion of found correlations. The datasets and maps that are used will be accessed through the shared data portal of the water board of Delfland and remain property of the water board of Delfland. They will be evaluated by using ArcGIS, Microsoft Excel and the knowledge of colleagues at the water board of Delfland.

2.1 Collecting data

Apart from data collected with fieldwork activities (expounded in **2.1.1** *Fieldwork*), data from earlier studies is used. The datasets from the shared data portal of the water board of Delfland that are used are: “Chemische dataset tbv kroosonderzoek IHE” (11658 measurements on 509 measurement locations), “Resultaten kroosmonitoring Delftse binnenstad” (3654 measurements on 63 measurement locations) and “Database metingen licht en gewicht onderzoek” (780 measurements on 12 measurement locations). The dataset “Chemische dataset tbv kroosonderzoek IHE” contains data on duckweed coverage and multiple other parameters, collected through fieldwork executed by Aquon (a Dutch institute for water research and advise) in the period of January 2014 to September 2019. The dataset “Resultaten kroosmonitoring Delftse binnenstad” contains data on duckweed coverage and some other parameters, collected through weekly monitoring in Delft, executed by the water board of Delfland in the period of June to October in 2018 and 2019. The dataset “Database metingen licht en gewicht onderzoek” contains (inter alia) data on duckweed coverage, light intensity and weight, collected through fieldwork activities executed by Ernst Raaphorst and Lesley Bezemer in the period of May to October in 2018.

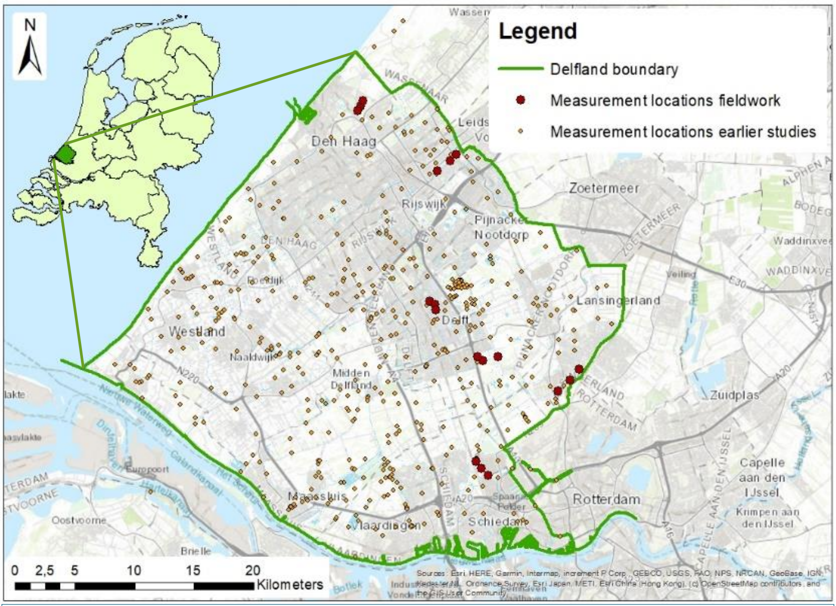

Figure 6: The area of Delfland (green) with the 18 measurement locations of the fieldwork (red) and all measurement locations of the Aquon dataset (orange).

The data from these three datasets is combined into one dataset, from here on further referred to as ‘the combined dataset’. The locations of all measurements from this dataset are shown in figure 6, in which the orange dots represent measurement locations from the combined dataset, while the red dots represent the measurement locations of the fieldwork executed for this research (expounded in **2.1.1** *Fieldwork*). In this research, a measurement location is defined as a location of which the precise position is recorded by means of X- and Y-coordinates and to which the results of measurements are allocated.

The maps from the shared data portal of the water board of Delfland that are used for this research are: “Kaart verspreiding” (January 2019, appendix III) and “NEZ network A3” (January 2019). Besides datasets and maps, aerial photographs are obtained from the shared data portal of the water board of Delfland from the years 2003, 2006 and 2008-2018 and infrared images from the years 2013-2018. The website "https://satellietdataportaal.nl/" is used to look at satellite images. Google Earth and Google Streetview are used as well, all providing information on the variance in duckweed coverage over time and space.

All data will be combined and analyzed using statistical methods to draw conclusions about the presence of duckweed in (the HEV-network of) Delfland and about the influence of duckweed on the ecological quality of a water body (expounded in 2.2 *Processing data*).

2.1.1 Fieldwork

Fieldwork is executed during four weeks in the period of September/October 2019 in collaboration with the water board of Delfland. A HQ40D Portable Multi Meter is provided by the water board of Delfland (figure 7 at the end of this paragraph). During the fieldwork period, duckweed is monitored in six potential duckweed-related problem areas within the HEV-network: Kwekerijweg the Hague, Broeksloot Voorburg, Rodenrijseweg Berkel, Karikaatmolensloot Delft, Polderweg Schiedam and Delft city center. These areas are chosen based on their important position within the HEV-network and on the knowledge of the water board of Delfland concerning duckweed coverage in these areas. They are viewed as the worst-case scenarios of the HEV-network. For each potential problem area, three specific measurement locations are determined in collaboration with the water board of Delfland, based on accessibility and (knowledge gaps in) previous studies. A total of 18 measurement locations will be monitored, as shown by the red dots in figure 6 on the previous page. For each location, fourteen parameters from the DPSIR framework are measured or estimated over the course of four weeks:

1. Time. This is recorded for every measurement location to account for natural oxygen and pH fluctuations during the day.
2. Temperature of the water in degrees Celsius. This is measured once every week by using the temperature indicator on the HQ40D Portable Multi Meter.
3. Water depth in centimeters. This is measured in the first and third week by using a measurement stick. The stick is put vertically into the water until the bottom is reached. The water depth can then be read from the stick. Per location, the two found values are averaged to determine the water depth.
4. Sludge depth in centimeters. This is measured in the first and third week by using a measurement stick. The stick is put vertically into the water until the bottom is reached. Then, the stick is pushed into the sludge until a harder surface underneath is reached. The sludge depth can then be read from the stick. Per location, the two found values are averaged to determine the sludge depth. The sludge depth and water depth are used to calculate the sludge ratio. This is calculated by dividing the sludge depth by the sum of water depth and sludge depth. The sludge ratio gives an indication of the sludge depth in relation to the water column.
5. pH. This is measured once every week by using the HQ40D Portable Multi Meter provided by the water board of Delfland.
6. Movement by wind. This is a combination of several parameters and will be scored on a scale of 0 to 5 using table 1 on the next page;
    - Wind speed. This is determined once every week by using the KNMI weather app, which shows the local wind speed and direction based on automatic measurements of the nearest of their 48 weather stations.
    - Wind direction. This is determined once every week by using the KNMI weather app, which shows the local wind speed and direction based on automatic measurements of the nearest of their 48 weather stations. The optimal wind direction is determined for every location at the start of the research, by looking at the position of the measurement location on the map.

   - Influence of wind. This is estimated once every week by using a matrix between zero and three (zero means no influence, one means very little influence, two means average influence, three means a lot of influence). In a closed off area, such as a canal surrounded by houses, the influence of wind is dependent on the wind direction. When the wind is blowing in a specific direction, it is expected to have more influence on duckweed coverage than in an open area with little or no obstructions. The wind speed and direction will only be taken into account when the influence of wind is one or more.

Table 1: Scoring of movement by wind by using the parameters 'wind speed', 'wind direction' and 'influence of wind'.

Movement by wind		Speed <10		Speed 10-20		Speed >20	
		Direction not optimal	Direction optimal	Direction not optimal	Direction optimal	Direction not optimal	Direction optimal
Influence of wind	0	0	0	0	0	0	0
	1	0	1	1	2	2	3
	2	1	2	2	3	3	4
	3	2	3	3	4	4	5

7. Movement by current. This is a combination of several parameters and will be scored on a scale of 0 to 5 using table 2;
   - Flow rate. The flow rate is estimated once every week by using a matrix between zero and three (zero means no flow rate, one means very low flow rate, two means average flow rate, three means high flow rate). On fast flowing water bodies a lower duckweed coverage is expected than on stagnant water bodies.
   - Connectivity. This parameter indicates the connectivity to bigger water bodies nearby and is estimated in the first week by using a matrix between zero and three (zero means no connection with bigger water bodies nearby, one means very little connection, two means average connection, three means an open connection). Water bodies with a high connectivity are expected to be less sensitive to (persistent) duckweed coverage than water bodies with a low connectivity.

Table 2: Scoring of movement by current by using the parameters 'flow rate' and 'connectivity'.

Movement by current		Connectivity			
		0	1	2	3
Flow rate	0	0	0	0	0
	1	0	1	2	3
	2	0	2	3	4
	3	0	3	4	5

8. Maintenance. This is assessed once every week by estimating whether the bottom is mowed or not. A possible correlation is that mowed water bodies contain less duckweed than water bodies that are not mowed, as there are less nutrients available if no other plant species are abundant. It is also possible that mowed water bodies contain more duckweed than water bodies that are not mowed, as competing species are removed and more nutrients are available for duckweed to grow.
9. Percentage of duckweed coverage or coverage with water fern in percentages. This is estimated once every week by looking at the surface of the water body and deducting coverage percentages. It is aspired to measure the coverage in a sample plot of 100m long, as prescribed by STOWA (2010). The coverage is divided into water fern and the four most commom species of duckweed in Delfland; gibbous duckweed (*Lemna gibba*), least duckweed (*Lemna minuta*), common duckweed (*Spirodela polyrhiza*) and rootless duckweed (*Wolffia arrhiza*), as described in 1.1 *Duckweed*.
10. Oxygen availability both in mg/L and in percentages. This is measured once every week by using the HQ40D Portable Multi Meter provided by the water board of Delfland.
11. Electrical Conductivity in µS/cm. This is measured once every week by using the HQ40D Portable Multi Meter provided by the water board of Delfland.
12. (sun)Light penetration in centimeters. This is measured twice during the fieldwork by using a secchi disk. The disk is lowered into the water body until the solid part of the disk can no longer

be told apart from the holes in the disk or until the bottom of the water body is reached. The secchi disk is provided by the water board of Delfland. In this research, (sun)light penetration is measured in terms of turbidity and not in terms of light intensity, see **3.2.2** *(sun)Light penetration*.

13. Attractiveness in terms of odor and color. This is a combination of two parameters and will be scored on a scale of 0 to 5 using table 3 on the next page;
    - Odor. This is assessed once every week using units as proposed by Aquo (2018). The units used in this research are: odorless, neutral, mouldy.
    - Color. This is assessed once every week using units as proposed by Aquo (2018). The units used in this research are: colorless, yellow, yellowish brown, brown, blackish brown.

Table 3: Scoring of attractiveness by using the parameters 'odor and 'color'.

Attractiveness		Color				
		Colorless	Yellow	Yellowish Brown	Brown	Blackish brown
Odor	Odorless	5	4	3	2	1
	Neutral	4	3	2	1	1
	Earthy	3	2	1	1	0
	Mouldy	2	1	1	0	0

14. Existence of dominant submersed and floating plant species. This is estimated twice during the fieldwork by looking at the coverage of submersed and floating vegetation in the water body. The coverage of submersed vegetation is measured in a sample area of $1m^2$, as prescribed by STOWA (2010). The coverage of floating vegetation is measured in a sample plot of 100m long, as prescribed by STOWA (2010). The dominant species that are distinguished are: hornwort (*Ceratophyllum demersum*), western waterweed (*Elodea nuttallii*), starwort (*Callitriche sp.*), common frogbit (*Hydrocharis morsus-ranae*), white water lily (*Nymphaea alba*) and yellow water lily (*Nuphar lutea*). These species are selected because they are known to be present in substantial numbers in Delfland and are considered dominant species.

From these fourteen parameters, parameter one through eight are considered drivers, parameter nine is considered the pressure parameter, parameters ten through thirteen are considered state parameters and parameter fourteen is considered an impact parameter.

Figure 7: Fieldwork setup for measuring pH, temperature, EC and oxygen availability.

Electrical Conductivity (EC) influences the growth of duckweed and can therefore be considered a driver parameter, yet as it is also influenced by the amount of duckweed coverage and influences growth of submerged aquatic plant species, it is considered a state parameter in this research.

Apart from these measurements, photographs are taken weekly on every location, to be able to compare the presence of duckweed over space and time. The data that is collected with the fieldwork activities will be documented in a Microsoft Excel file before it is analyzed and compared to earlier data or literature. A setup of some of the fieldwork measurements is shown in figure 7.

2.2 Processing data

The correlations between the five relevant driver parameters (nutrients, temperature, sludge depth, pH and movement) and duckweed coverage are calculated by executing a multiple regression analysis with the regressions statistics option in Microsoft Excel. All regression analyses in this research are based on some assumptions: the correlations between the dependent and independent variables are linear, data is obtained with random sampling, residuals are normally distributed, independent variables have no strong reciprocal linear relation to each other, variance in the dependent variables is not caused by variance in the correlation and standard deviations of the error terms are constant and do not depend on the value of the independent variable.

A multiple regression analysis is performed, using the driver parameters as independent variables and duckweed coverage as dependent variable. Microsoft Excel returns inter alia the coefficient of determination (R^2), the probability value per parameter (P) and the slope of each correlation. These values indicate the amount of variance in the dependent variable that is correlated to variance in the independent variables, the significance of the correlation and the expected increase/decrease in the dependent variable with an increase of one measurement unit in the independent variable. The regression analysis will be executed multiple times with different data; once with data from the fieldwork and multiple times with different selections of data from the combined dataset. The first selection contains all data from the combined dataset, the second selection contains only data that is collected during the peak of the duckweed growth season (July-September) and the third selection contains all data except the measurements with 5% duckweed coverage. The second selection of the data is made because a T-test showed significant differences between duckweed coverage values in the peak of the duckweed growth season (July-September) and in the remaining months. The last selection of the data is chosen because upon perusing the dataset it was found that a lot of measurements contained a duckweed coverage of 5%. This is considered unrealistic and is expected to weaken the correlations. It is decided not to make a selection of the dataset only containing polders or storage basins, as a T-test showed no significant differences in duckweed coverage between both water types. The regression analyses will confirm or dismiss statistical relations between the five driver parameters and duckweed coverage. Literature is reviewed to compare the found relations with relations found by others.

The correlations between duckweed coverage (pressure) and four relevant state parameters (oxygen availability, (sun)light penetration, Electrical Conductivity and attractiveness) are calculated by executing a multiple regression analysis with the regressions statistics option in Microsoft Excel. A multiple regression analysis is performed, using duckweed coverage as independent variable and the state parameters as dependent variables. Microsoft Excel returns inter alia the coefficient of determination (R^2), the probability value per parameter (P) and the slope of each correlation. The regression analysis will be executed multiple times with the same selections of the data as described above. The regression analyses will confirm or dismiss statistical relations between duckweed coverage and the four state parameters. Literature is reviewed to compare the found relations with relations found by others.

Generally, in accordance with the WFD, assessments of the ecological water quality of a water body are based on the abundance of microorganisms and species of macrophytes, macroinvertebrates and fish in that water body (STOWA, 2009). For this research, microorganisms are not considered as their growth conditions and life-cycles are very complex and the HEV-zones are focused on improving the circumstances for the growth of macro species, thus they are the main focus of this study. The impact of the state parameters on macrophytes, macroinvertebrates and fish is studied through literature review to provide a simplified estimation of the impact of duckweed on the EWQ.

Information about the current duckweed coverage in six potential problem areas in Delfland is obtained with fieldwork activities (see 2.1.1 *Fieldwork*). The found values for duckweed coverage will be assimilated in maps using ArcGIS. Variance in duckweed coverage over time on these six areas will be researched by looking at satellite images of multiple years from Google Earth, Google Streetview and the website "https://satellietdataportaal.nl/". Also, aerial photographs from the years 2003, 2006 and 2008-2018 and infrared images from the years 2013-2018 are obtained from the shared data portal of the water board of Delfland. The exact dates of the aerial photographs and infrared images are unknown; thus, estimations are made. Based on all these sources, for each date of which one or more source is available, estimations are made on the coverage (no distinction could be made between duckweed coverage and other types of coverage). Coverages of 0% are noted as 0.5% to distinguish them from 'no data' values. Daily temperature data is obtained from the Rotterdam weather station (the closest weather station of the Koninklijk Nederlands Meteorologisch Instituut (KNMI) to the fieldwork locations) from the website "https://weerstatistieken.nl/rotterdam/". Graphs are made per area to show coverage- and temperature variance over the years.

For the city center of Delft, extra data points have been added to the analysis of duckweed coverage variance over time, by copying data from the dataset "Resultaten kroosmonitoring Delftse binnenstad" (which is also used for the first part of this research); data point 62 of the monitoring data corresponds to measurement location 1 of this research, data point 56 corresponds to measurement location 2 and data point 47 corresponds to measurement location 3. For the Polderweg Schiedam, extra data points have been added by copying data from an earlier study by Raaphorst (2019b). Data point A003 of his research corresponds to measurement location 2 of this research and data point A001 corresponds to measurement location 3.

Measurement locations of the fieldwork that show an abundance of duckweed and/or water fern of >75% will be marked as a duckweed-related problem location, as well as measurement locations that have shown a coverage of >75% in previous years (no distinction could be made between duckweed coverage and other types of coverage). From the aerial photograph of 2018 and the infrared image of 2018, ten locations are searched that show duckweed. These locations are examined more closely by looking at the aerial photographs and infrared images of other years. From those ten locations, the locations that show >75% coverage in more than one year are marked as a problem location. Data points from the dataset "Chemische dataset tbv kroosonderzoek IHE" with a duckweed coverage of >75% are also marked as problem locations.

The found problem locations are added into a map with duckweed-related problem locations of an earlier study by Bezemer (2019), containing problem locations obtained from literature, complaints from residents and complaints from operational water level managers. Intersecting problem locations will be marked on the map with a green diamond. The map is combined with a map of the HEV-zones to analyze the severeness of the found problem locations.

3. Duckweed and the ecological water quality

Duckweed can store relatively little amounts of energy reserves, making them dependent on a stable, nutrient rich environment (STOWA, 2014). Grown duckweed can not survive enduring food shortages. However, in convenient environments, duckweed can grow much faster than competing floating aquatic plants. Each individual leaflet (frond) produces about 20 daughter fronds during its lifetime. This results in exponential growth until the plants run out of space or nutrients (Vymazal et al., 1998). Under ideal growth conditions, biomass of duckweeds gets doubled in 2–3 days (Iqbal 1999; Skillicorn et al., 1993; STOWA, 1993). Ideal growth conditions of duckweed consist of nutrient availability, sunlight, a pH between 5.9 and 7.4, a photoperiod of 12-13h and a temperature between 20°C and 31°C (STOWA, 2014; Lasfar et al., 2007; Landolt, 1987). Duckweed usually grows in the period april-june, peaks in the period july-september and naturally breaks down in the period oktober-december (STOWA, 2014). To survive longer periods of food scarcity, duckweed can form so-called “turions”, which can survive through winter in the bottom layer of a water body (STOWA, 2014). Some species of duckweed, such as *Azolla, Lemna minor* and *Lemna minuta*, can survive short periods of frost and do not necessarily die off completely during winter. This causes them to be able to start growing again early in the season.

Rising atmospheric temperatures due to climate change are causing the growth period to start earlier and thus lengthen. An increase of the atmospheric temperature of one degree Celsius is enough to accelerate the start of the growth season of duckweeds by two weeks (Peeters et al., 2013). Figure 8 is copied from STOWA (2014) and shows the average coverage of duckweed in the Netherlands per month in the period of 1980 to 2008, based on data from the Limnodata Neerlandica, which is a dataset that at the time consisted of almost 16000 observations.

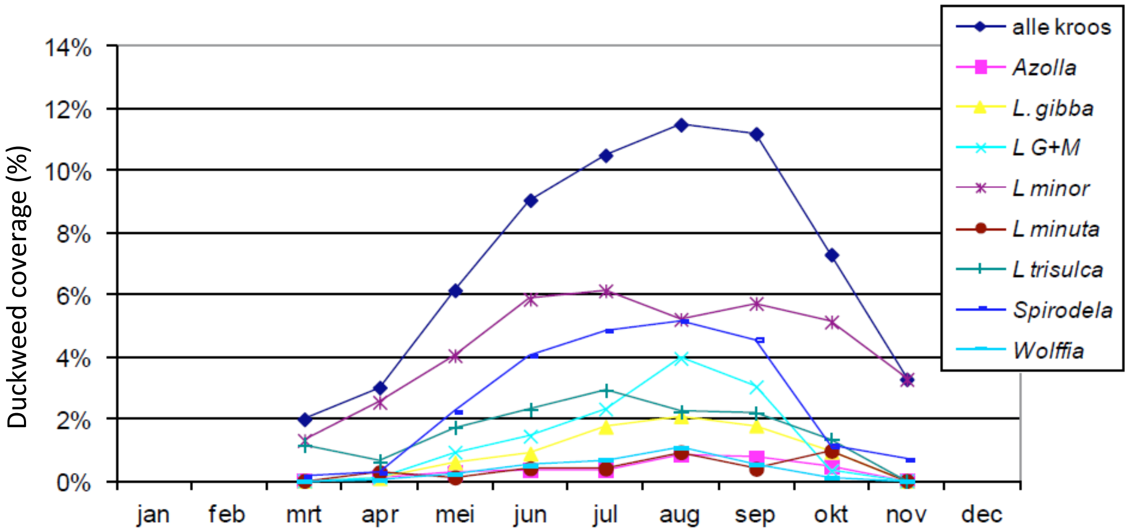

Figure 8: Duckweed in the Netherlands per month in the period 1980-2008. Source: STOWA, 2014.

The results regarding the correlations between driver parameters and duckweed coverage and the correlations between duckweed coverage and state parameters are described in the following two paragraphs. The impact of the state parameters on the EWQ will be described in paragraph 3.3 *Ecological water quality*.

3.1 Driver parameters

Driver parameters refer to the independent, external causes (or forces) that underlie movement toward or away from desired targets (Chorley and Kennedy, 1971; Parris and Kates, 2003). In this research, the drivers are parameters that (directly) affect duckweed growth: nutrients, temperature, sludge depth, pH, movement by wind and movement by current. The value for the parameter movement by wind is determined by combining the parameters wind speed, (optimal) wind direction and influence of wind. The value for the parameter movement by current is determined by combining the parameters flow rate and connectivity. The parameter maintenance produced no results as not enough data could be gathered to perform regression analyses. It was therefore decided to disregard the parameter maintenance in this research.

A multiple regression analysis with the data collected during the fieldwork showed that 22.3% of the observed variance in duckweed coverage is explained by variance in the parameters temperature, sludge depth, pH, movement by wind and movement by current ($p<.05$). A multiple regression analysis with the data from the combined dataset showed that 9.4% of the observed variance in duckweed coverage is explained by variance in the parameters phosphorus, nitrogen, temperature and pH ($p<.05$). With the data from the combined dataset that is collected during the peak of the duckweed growth season, this value increased to 13.0%. After eliminating the measurements with a duckweed coverage of 5%, a multiple regression analysis with the data from the combined dataset showed that 14.5% of the observed variance in duckweed coverage is explained by variance in the parameters phosphorus, nitrogen, temperature and pH ($p<.05$). The results of the analyses are summarized in table 4 and are discussed in the following paragraphs.

Table 4: Increase in duckweed coverage (%) per increase of one parameter unit. Shown values are significant with $p<.05$ and rounded to two decimals.

Parameters	Literature	Fieldwork data			Combined dataset			Combined dataset (summer)			Combined dataset (coverage≠5%)		
		Slope	Lowest 95%	Highest 95%	Slope	Lowest 95%	Highest 95%	Slope	Lowest 95%	Highest 95%	Slope	Lowest 95%	Highest 95%
Nitrogen (mg/L)	Positive correlation	-			-0.14	-0.23	-0.06	-0.29	-0.54	-0.05	-0.58	-1.07	-0.08
Phosphorus (mg/L)	Positive correlation	-			1.57	1.15	2.00	5.10	3.60	6.50	4.05	1.55	6.55
Temperature (°C)	Positive correlation	Not significant			0.50	0.43	0.56	Not significant			1.06	0.52	1.60
Sludge depth (cm)	Positive correlation	0.75	0.11	1.38	-			-			-		
pH (-)	Negative correlation	Not significant			-8.11	-8.81	-7.40	-14.50	-16.31	-12.67	-27.42	-32.35	-22.49
Movement by wind (scale of 0-5)	Negative correlation	-12.52	-19.09	-5.95	-			-			-		
Movement by current (scale of 0-5)	Negative correlation	Not significant			-			-			-		

3.1.1 Nutrients

Compared to the potential biomass of submerged vegetation, the biomass of duckweed is small. In water bodies with a low nutrient concentration, submerged plants can therefore more easily grow and they can exhaust the water body from nutrients, so that duckweed is at a disadvantage (STOWA, 2014). For the same reason, when a water body is moderately enriched with nutrients, the first effect is an increase of submerged vegetation biomass (Janse & Puijenbroek, 1998). Further eutrophication often stimulates the blooming of filamentous and/or epiphytic algae. The resulting decreased light availability causes a shift from species with a vertical growth strategy to those with a horizontal growth strategy (Sand-Jensen & Sondergaard, 1981; Bloemendaal & Roelofs, 1988) and the biodiversity diminishes. At very high nutrient loading, the vegetation becomes dominated by a surface layer of pleustophytic (unattached, floating) plants only, such as duckweed (*Lemnaceae*) or water fern (*Azolla filiculoides*), while submerged plants have disappeared (Portielje & Roijackers, 1995; Eugelink et al., 1998). Simulations with a model called 'PCDitch', previously calibrated on experimental ditches, indicate that this switch may occur as soon as a certain critical nutrient loading level is exceeded (Janse & Puijenbroek, 1998). This level tends to increase with flow rate and water depth, except for very shallow ditches (figure X). In the study of Liere et al. (2007), The critical values for phosphorus and nitrogen are calculated for an average ditch with a depth of 0.5 meters and a flow rate of 30 mm/day using the model PCDitch. The found values were 0.23 mg/L and 1.40 mg/L for phosphorus and nitrogen, respectively.

The oxygen that is produced by the pleustophytic plants is released into the atmosphere instead of into the water and reaeration is obstructed, while decomposition continues to extract oxygen from the water. Because of this, the water often becomes anoxic (Veeningen, 1982; Marshall, 1981; Portielje, 1994) causing various other problems, see 3.2.1 *Oxygen availibility*.

Several authors showed a positive correlation between duckweed cover on one hand and nutrient concentrations (e.g. nitrogen and phosphorus) in the water on the other (Groot et al., 1987; Does & Klink, 1991; STOWA, 1993; BKH Adviesbureau, 1995). Water fern can even increase the nitrogen values in a water body as it fixates nitrogen from the atmosphere and releases it into the water upon wilting (Hiscock, 2003; STOWA, 2014). However, the correlations described in literature were often obscured by (all positive) correlations with other factors, such as biological oxygen demand, conductivity and pH (Does & Klink, 1991). Nutrient concentrations are shown not to be the most important limiting condition for duckweed growth (STOWA, 2014). Besides, in most parts of the Netherlands, waters are considered to be eutrophic in the standard situation and structural reduction of eutrophication is not considered feasible. To compensate the increased growth conditions by climate change (through increased temperatures, see the introduction of chapter 3 *Duckweed and the ecological water quality*), massive reduction of nutrients is needed (Peeters et al., 2013).

Nutrient values were not measured in the fieldwork of this research, partly because there were no means to do so and partly because in the study of STOWA (2014), it was found that the three most abundant (in combination with duckweed) submerged plant species are limited by the same chemical composition as duckweed itself. This suggests chemical composition is not the most important component in the competition between duckweed and submerged plants. This also suggests reducing the eutrophication will not suffice as a single measure against duckweed coverage. Other factors, such as temperature, sludge ratio, pH and movement should be taken into account as well. For this fieldwork research, it was decided that possible differences in nutrient values could be neglected.

Nutrient values for Nitrogen and Phosphorus were included in the data from the combined dataset thus regression analyses with these values were conducted. Significant ($p<.05$) negative correlations were found between nitrogen concentrations and duckweed coverage for all three selections of the combined dataset, indicating a decrease in duckweed coverage with an increase of nitrogen. This is in contrast with literature, which suggested a positive correlation. This could be explained by the influence of a third parameter that is not considered in this research. A multiple regression analysis with the complete combined dataset showed a correlation in which an increase of nitrogen with 1 mg/L corresponds to a decrease in duckweed coverage with 0.14%, with a 95% certainty range of -0.06% to -0.23% (see table 4 on page 18). With the data from the combined dataset that is collected during the peak of the duckweed growth season, a significant (p<.05) negative correlation was found between duckweed coverage and nitrogen concentrations in which an increase of nitrogen with 1 mg/L corresponds to a decrease in duckweed coverage with 0.29%, with a 95% certainty range of -0.05% to -0.54%. With the data from the combined dataset that contains a value for duckweed coverage different than 5%, a significant (p<.05) negative correlation was found in which an increase of nitrogen with 1 mg/L corresponds to a decrease in duckweed coverage with 0.58%, with a 95% certainty range of -0.08% to -1.07%. These values are all quite low, indicating a weak negative correlation between nitrogen concentrations and duckweed coverage.

Significant (p<.05) positive correlations were found between phosphorus concentrations and duckweed coverage for all three selections of the combined dataset (see table 4 on page 18), indicating an increase in duckweed coverage with an increase of phosphorus. This is in alignment with literature. A multiple regression analysis with the complete combined dataset showed a correlation in which an increase of phosphorus with 1 mg/L corresponds to an increase in duckweed coverage with 1.57%, with a 95% certainty range of 1.15% to 2.00%. With the data from the combined dataset that is collected during the peak of the duckweed growth season, a significant (p<.05) negative correlation was found between duckweed coverage and phosphorus concentrations in which an increase of phosphorus with 1 mg/L corresponds to an increase in duckweed coverage with 5.10%, with a 95% certainty range of 3.60% to 6.50%. With the data from the combined dataset that contains a value for duckweed coverage different than 5%, a significant (p<.05) negative correlation was found in which an increase of phosphorus with 1 mg/L corresponds to an increase in duckweed coverage with 4.05%, with a 95% certainty range of 1.55% to 6.55%. These values are quite high, especially for the data from the combined dataset that is collected during the peak of the duckweed growth season and the data from the combined dataset that contains a value for duckweed coverage different than 5%, indicating a quite strong positive correlation between phosphorus concentrations and duckweed coverage.

3.1.2 Temperature

Temperature is one of the most important aspects in the aquatic ecosystem as it plays a key role in determination of other parameters such as conductivity, saturation stage of gases and different forms of alkalinity (Esmaeili & Johal, 2005; Singh & Mathur, 2005). It is perhaps the most significant environmental factor impacting fish survival and habitat selection (Beitinger et al., 2000).

Duckweed can grow at water temperatures ranging from 5 to 35°C with a positive correlation between water temperature and duckweed growth (Oron & Willers, 1989; Wedge & Burris, 1982) up to an optimum temperature, above which duckweed growth decreases again (see figure 9). The optimum growth was found to be between 20 and 31°C depending on the species (Boniardi et al., 1999; Frederic et al., 2006; Iqbal, 1999; Lasfar et al., 2007; Zirschky & Reed, 1988). Within this range, duckweeds reproduce quickly until total consumption of nutrients. However, in the vicinity of 45 °C, duckweed growth is strongly inhibited (Filbin & Hough, 1985). Above this temperature, the plant growth is slowed down and even stopped (Boniardi et al., 1999; Iqbal 1999; Oron and Willers, 1989; Zirschky and Reed, 1988).

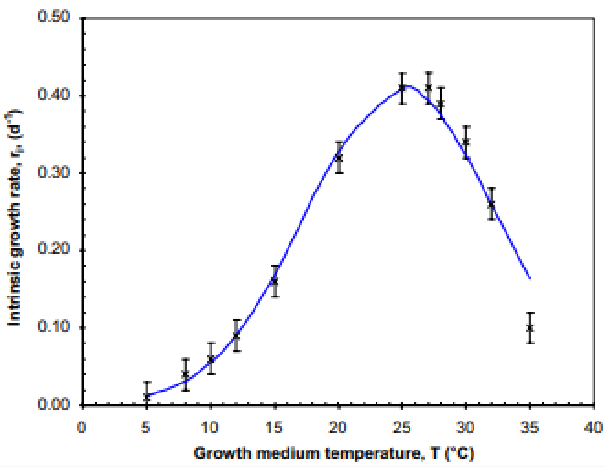

Figure 9: Optimum duckweed growth temperature. Source: Lasfar et al. (2007)

In the study of Carvalho et al. (2005), a significant positive correlation was found between temperature and the decomposition rate of submerged macrophytes. Carpenter & Adams (1979) also found an increase in the decay coefficient of the submersed aquatic macrophyte *Myriophyllum spicatum* following an increase in temperature to 28°C. Apart from the decomposition rate, Carvalho et al. (2005) found correlations between temperature and other parameters: with a higher temperature the microbial activity increased, which increased oxygen consumption in the water, consequently affecting the pH and the rate of ion and nutrient liberation to the aquatic ecosystem.

From the data collected during the fieldwork, no significant correlation was found between the temperature of the water and the duckweed coverage (see table 4 on page 18). From the data from the complete combined dataset, a weak yet significant positive correlation was found ($p<.05$), in which an increase in temperature with 1°C corresponds to an increase in duckweed coverage of 0.50% with a 95% certainty range of 0.43% to 0.56%. This is in alignment with the correlation described in literature. With the data from the combined dataset that is collected during the peak of the duckweed growth season, no significant correlation was found. This could be explained by the high temperatures in those months, where no limitation by temperature takes place. With the data from the combined dataset that contains a value for duckweed coverage different than 5%, a significant positive correlation was found ($p<.05$) in which an increase in temperature with 1°C corresponds to an increase in duckweed coverage of 1.06% with a 95% certainty range of 0.52% to 1.60%. The slope values for the correlation between temperature and duckweed coverage are low, indicating a weak correlation. However, the magnitudes of the found correlations are in alignment with literature.

3.1.3 Sludge depth

Eutrophication causes degradation through a cascade of effects which cumulate into the formation of a thick layer of fine organic sludge (Lamers et al., 2002). A thick layer of sludge can have negative impacts on aquatic invertebrates (Verberk et al., 2007). Shelter, oviposition substrate, and food for herbivores are no longer provisioned by submerged macrophytes. Low oxygen levels, high sulphide levels or release of toxic substances by cyanobacteria can increase mortality, leading to a loss of habitat diversity (Higler 1977). In the study of Verberk et al. (2007), a comparison between dredged and undredged water bodies showed coverage of submerged vegetation was higher in dredged water bodies than in undredged water bodies. This suggests sludge has a negative relation with submersed vegetation growth.

On the contrary, STOWA (2014) stated that the sludge depth has a positive relation with the duckweed coverage; a thicker sludge layer results in a larger duckweed coverage. A thick layer of sludge is also an indicator of eutrophication, which is in line with duckweed growth (see **3.1.1** *Nutrients*). In the study of STOWA (2014), a dataset with 1416 observations was analyzed and on average a duckweed coverage of 39.4% was found at water bodies with a sludge depth of >20cm, while with a sludge depth of 5-20 cm and <5 cm, only 23.1% and 12.5% of the water bodies was covered in duckweed, respectively.

By executing a multiple regression analysis with the data collected during the fieldwork, it was found that sludge depth has a significant positive correlation to variance of duckweed coverage ($p<.05$). In this correlation, an increase of 1 cm in sludge depth corresponds to an increase in duckweed coverage of 0.75% with a 95% certainty range of 0.11% to 1.38% (see table 4 on page 18). This value is low; therefore, the correlation is considered weak, but the magnitude of the correlation is in alignment with the magnitude of the correlation described in literature. Converting sludge depth into sludge ratio by integrating the water depth showed similar results. In the combined dataset, sludge depth was only recorded 5 times so no analysis could be done.

3.1.4 pH

The pH measures the acidity or alkalinity of water, with a pH of 1 being strongly acidic, a pH of 7 being neutral, and a pH of 14 being strongly alkaline (Queensland Government, 2018). Generally, the pH of fresh surface waters is between 6.5 and 8.0. The pH can be influenced by many factors, for example, an algal bloom can increase pH readings to 9.5 (Queensland Government, 2018).

The pH of water (external pH) has a positive feedback effect on the cytoplasmic pH (pHc) and the vacuolar pH (pHv) of plant cells in anoxic conditions (Fox et al., 1995). Under normal conditions, the pHc and pHv of typical plant cells are maintained at slightly alkaline (typically 7.5) and acidic (typically 5.5) values, respectively (Ishizawa, 2014). As discussed in 'oxygen availability', a failure to maintain the pH homeostasis of cells (caused by an increase/decrease in external pH) can lead to cell death (Roberts et al., 1984).

Several experiments in the study of McLay (1974) suggested that a lowered growth rate of duckweed was attributable to a higher pH of the water, probably produced by the photosynthesis of other aquatic plants. McLay confirmed this hypothesis in a later study (1976), where he experimented with buffered media and found that both duckweed species *Spirodela; oligorrhiza* and *Lemna minor,* tend to grow at their maximum rate between pH 5 and pH 8 and duckweed growth is slowed down and even stopped at lower or higher pH values. Consenting results are found in the study of Landolt (1987). In this study it was stated that duckweed grows best in the pH range of 5.9 to 7.4, whereas extreme pH values may cause direct growth inhibition. At pH lower than 6 biomass production was observed, but the fronds appeared unhealthy, wrinkled and yellowish (this was confirmed by the study of Caicedo et al., 2000). At pH values above 8, duckweed was observed to die off. The optimal pH value reported in this study for the growth of *Spirodela polyrrhiza* is around 7 and this was confirmed by the studies of Caicedo et al. (2000), Bitcover and Sieling (1951) and Landolt (1987).

From the data collected during the fieldwork, no significant correlation was found between pH and duckweed coverage (see table 4 on page 18). From the data from the complete combined dataset, a significant negative correlation was found ($p<.05$), in which an increase of 1 in pH corresponds to a decrease in duckweed coverage of 8.11% with a 95% certainty range of -8.81% to -7.40%. With the data from the combined dataset that is collected during the peak of the duckweed growth season, a significant negative correlation was found ($p<.05$), in which an increase of 1 in pH corresponds to a decrease in duckweed coverage of 14.50% with a 95% certainty range of -16.31% to -12.67%. With the data from the combined dataset that contains a value for duckweed coverage different than 5%, a significant ($p<.05$) negative correlation was found in which an increase of 1 in pH corresponds to a decrease in duckweed coverage of 27.42% with a 95% certainty range of -32.35% to -22.49%. These values are quite high, indicating a quite strong negative correlation between pH and duckweed coverage, which is in alignment with literature.

3.1.5 Movement (by wind and current)

Because duckweed is a free-flowing plant, it is influenced by current and wind (STOWA, 2014). In general, duckweed is not present on big lakes or fast flowing water bodies. In long ditches or canals, duckweed can be transported due to influence of wind and/or accumulated on one side. This means coverage with duckweed in those areas can be temporary; varying in time and space.

In ditches or canals with a high flow rate, plants have to anchor themselves to the ground in order to prevent flushing out (STOWA, 2010). Duckweed does not apply this strategy and will therefore only grow in areas where the flow rate is low. The movement of water in terms of billow also plays a role in the growth of aquatic plants (STOWA, 2010), but this is not relevant for this study since none of the researched waters experience billow. In ditches with a low connectivity, duckweed can not be flushed out easily, making it a vulnerable environment as duckweed can easily develop and spread. Coverage with duckweed in those areas can be stationary.

A multiple regression analyses with the fieldwork data showed a significant negative correlation between movement by wind and duckweed coverage ($p<.05$). An increase in movement by wind with one (on a scale of zero to five) corresponds to a decrease in duckweed coverage of 12.52% with a 95% certainty range of -19.09% to -5.95% (see table 4 on page 18). This value is not extremely high, indication a correlation that is not very strong, but it is in alignment with literature. The correlation between movement by current and duckweed coverage was not significant. In the combined dataset, movement was not registered thus no regression analyses could be executed.

3.2 State parameters

State variables describe the condition or observable changes in the system following the pressure (Ness et al., 2010). During the fieldwork period one of the state parameters, attractiveness in terms of odor and color, was found to be equivalent in almost all measured water bodies. Due to this low variety in attractiveness, a correlation with duckweed coverage cannot be proven based on the fieldwork results. In the combined dataset, no odor values were recorded, thus attractiveness could not be valued. It was therefore decided to disregard the parameter attractiveness in this research. The state parameters are thus represented in this research by oxygen availability, (sun)light penetration and electrical conductivity. Correlations between duckweed coverage and the state parameters are deducted from literature, the fieldwork data and the data from the combined dataset. With the data from the combined dataset, several selections are made in an attempt to find stronger correlations; see 2.2 *Processing data*.

The separate effects of duckweed coverage on the state parameters oxygen availability, (sun)light penetration and electrical conductivity are summarized in table 5 below and discussed in the following paragraphs. The correlations between the state parameters and the EWQ are summarized in table 6 and discussed in 3.3 *Ecological water quality*.

Table 5: Increase in parameter unit per increase of one % duckweed coverage (slope). Shown values are significant with p<.05 and rounded to two decimals.

Parameters	Literature	Fieldwork data		Combined dataset		Combined dataset (summer)		Combined dataset (coverage≠5%)	
		Slope	Lowest 95% / Highest 95%	Slope	Lowest 95% / Highest 95%	Slope	Lowest 95% / Highest 95%	Slope	Lowest 95% / Highest 95%
Oxygen availability (mg/L)	Negative correlation	-86.11	-160.95 / -11.26	-1.11	-1.36 / -0.87	-2.11	-3.83 / -0.40	-4.74	-7.33 / -2.16
Oxygen availability (%)	Negative correlation	7.70	0.67 / 14.73	Not significant		Not significant		Not significant	
(sun)Light penetration (cm)	Negative correlation	Not significant		-0.03	-0.04 / -0.02	-0.04	-0.07 / -0.02	-0.20	-0.27 / -0.13
Electrical Conductivity (µS/cm)	Positive and negative correlation	Not significant		Not significant		Not significant		Not significant	

Table 6: Correlations between state parameters and the ecological water quality in terms of macrophytes, macroinvertebrates and fish, according to literature.

Parameters	Macrophytes	Macroinvertebrates	Fish
Oxygen availability	Positive correlation	Neutral	Positive correlation
(sun)light penetration	Positive correlation	Positive correlation	Neutral
Electrical Conductivity	Positive correlation	Negative correlation	Neutral / Negative correlation

3.2.1 Oxygen availability

Oxygen concentrations, like pH, naturally fluctuate over time, showing a peak in the late afternoon and a depression in the early morning (figure 10, STOWA, 2014). However, the oxygen concentration in a water body is also impacted by other factors such as duckweed coverage.

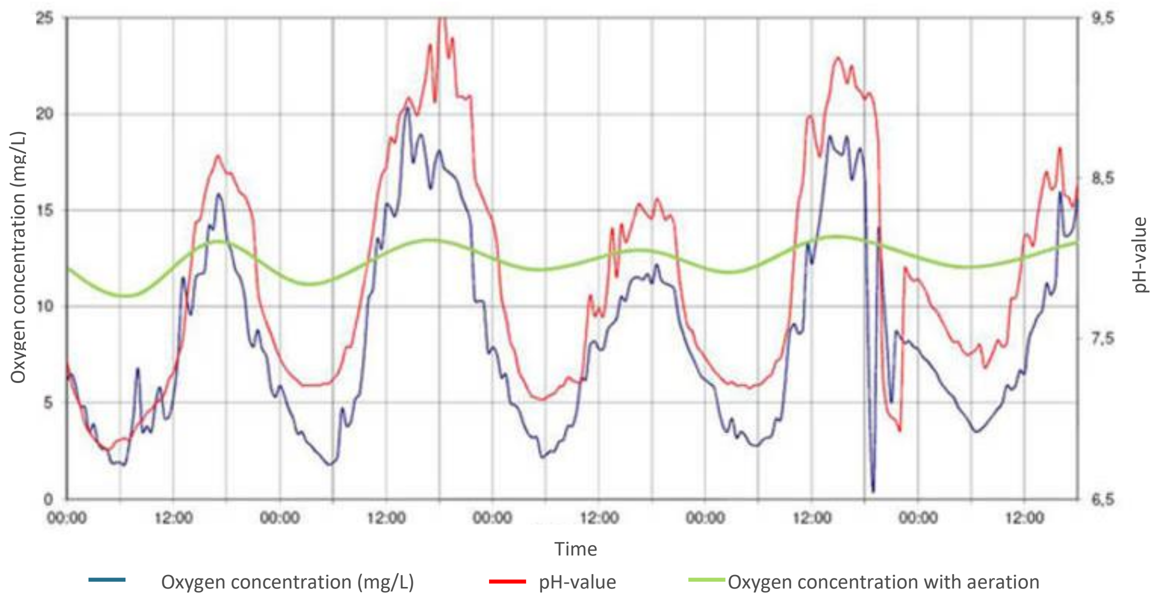

Figure 10: Oxygen concentration and pH value depending on time of day in a small pond (1000 liters) without water circulation. Source: STOWA, 2014

As an effect of duckweed coverage on a water body, (sun)light is no longer able to reach under water, which causes photosynthesis to cease and oxygen to no longer be produced by submersed plant species (Srivastava et al., 2008; STOWA, 2014). Also, the decrease in (sun)light penetration influences the temperature, which in turn influences the oxygen concentration (Raines & Miranda, 2016). Duckweed itself produces oxygen, but does not release this oxygen into the water (Pokorný & Rejmánková, 1983). On top of this, oxygen exchange between the water body and the atmosphere is blocked by the duckweed (Srivastava et al., 2008; STOWA, 2014). Thus, oxygen is no longer produced or exchanged but still used, resulting in low dissolved oxygen levels in the water.

In the study of STOWA (2014), the effects of seven species of duckweed and three species of submersed plants on oxygen concentrations are studied. In figure 11 on the next page the observed oxygen concentrations (in %) of this study are presented. The oxygen concentrations were found to be lower than 100% in over 90% of the studied waters that were covered in duckweed. Deep oxygen deficiencies, however, were rarely observed. In only 0.5% of the observations, an oxygen concentration of <2 mg/L was measured. The average oxygen concentration in duckweed-covered waters in this study was 66.9%. In the studied water bodies where submerged plants existed, much higher oxygen concentrations were found, with an average of 79.3%.

In aerobic organisms, such as plants, oxygen is a rate-limiting substrate for the efficient production of energy (Kosmacz & Weits, 2014). Despite their ability to produce oxygen in the presence of light, plants can experience low oxygen conditions when the oxygen diffusion from the environment cannot satisfy the demand set by metabolic rates. Plant cells exposed to anaerobic conditions manifest various kinds of symptoms (Ishizawa, 2014). Most of these symptoms are related to the deterioration of energy metabolism under anoxia and the resulting collapse of intracellular homeostasis, which leads to cell death.

Apart from energy, the cytoplasmic pH of a plant is also depending on oxygen availability (Ishizawa, 2014). In most organisms, including plants, when a cell is exposed to anoxic conditions, the cytoplasmic pH drops rapidly and reaches a transient stationary value (Roberts et al., 1984; Raven, 1986; Kennedy et al., 1992; Ratcliffe, 1997). The strength of anoxia tolerance can be expressed as the duration of this stationary phase. Death was reported to occur in anoxic sycamore cells when the cytoplasmic pH decreased below 6.5 in the study of Gout et al. (2001). In this study, cytoplasmic pH decreased from 7.5 to 6.8 within 4 to 5 minutes after the onset of anoxia, whereas vacuolar pH (5.7) and external pH (6.5) remained stable. Following re-oxygenation, the cytoplasmic pH recovered its initial value within 2 to 3 minutes, whereas external pH decreased abruptly. Whether this reaction of cytoplasmic and external pH values to anoxia can be universally adopted remains unclear.

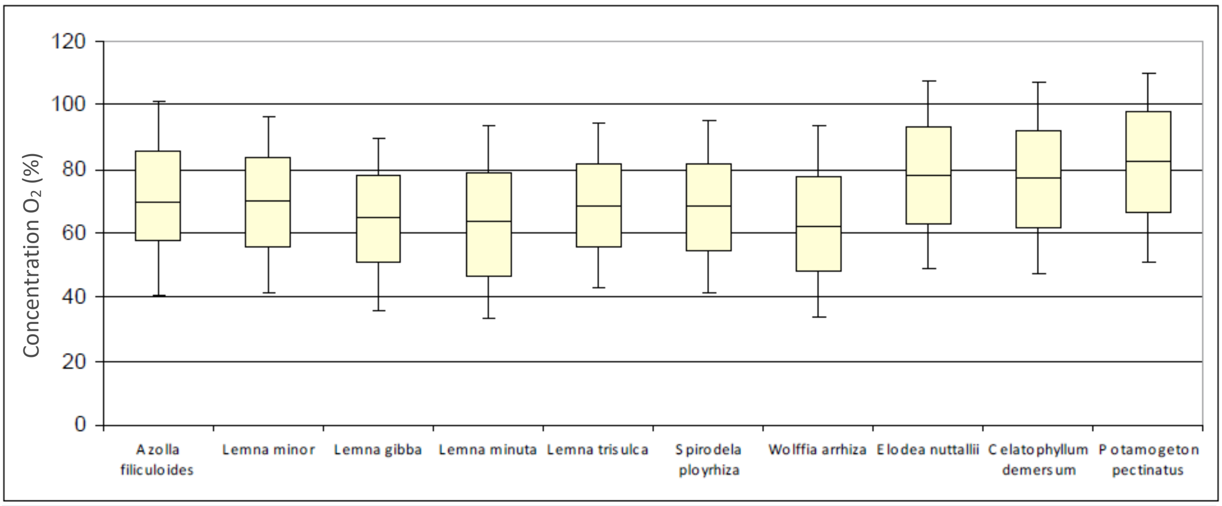

Figure 11: Average oxygen concentrations (90 percentile, 75 percentile, median, 25 percentile and 10 percentile) in water bodies covered with seven common duckweed species and three species of submersed aquatic plants. Source: STOWA, 2014. Limnodata Neerlandica

The capacity of plant species living in aquatic and marsh habitats to survive in anoxic conditions is found to be vary variable (Crawford & Brändle, 1996; Crawford 1992; Drew 1990). In some species, tolerance of anoxia is extremely well developed; not only can the rhizomes survive several weeks without any oxygen, they can also extend new shoots (Brändle and Crawford, 1987; Crawford, 1989). As a result of prolonged tolerance of anoxia, submerged rhizomes that have lost last season's dead stalk, which acts as a snorkel connecting them with a supply of air (Brix, 1989), can still emerge in spring from an entirely oxygen-deficient habitat. Other species can survive long periods without any oxygen, but only begin shoot extension once the oxygen supply is restored (Barclay and Crawford, 1982). In 2012, Lemoine et al. studied the resistance to sediment anoxia of three aquatic oligotrophic macrophyte species (*Potamogeton coloratus, Elodea canadensis* and *Sparganium emersum*) under laboratory conditions. All three species suffered net biomass loss and depressed their photosynthesis rates under anaerobic conditions.

For macroinvertebrates, the effects of anoxia seem less detrimental. In the study of Hammen (1976), survival of prolonged anoxia was recognized as a common feature of invertebrate respiration. The effects of anoxia on aquatic macroinvertebrates were studied inter alia by Kornijów et al. (2010). In this study, nine sites in the freshwater tidal Hudson River in New York, which was covered with a dense bed of water-chestnut (*Trapa natans*, a duckweed-like, floating-leaved plant), were sampled in June and July to look at invertebrates and dissolved oxygen. In June, the water-chestnut canopy was not fully developed and hypoxia was only moderate, while in July the canopy was fully developed and hypoxia was frequent and severe. In both circumstances, dense and diverse communities of invertebrates were found, including insects, oligochaetes, crustaceans, and other taxa. Based on these results, anoxia seems to have no negative effects on macroinvertebrates. Also in the study of Jacobsen et al. (2003), where macroinvertebrates in lowland streams (where oxygen values are sufficient) are compared to macroinvertebrates in highland streams (where oxygen is deficient), no statistic differences were found (p<.05). Similar results were found in the study of Acharyya & Mitsch (2001), where water boatmen (*corixidae*) were found to be pollution tolerant species which can tolerate highly anoxic conditions. According to Peckarsky (1984), water boatmen tend to replace species sensitive to pollution or anoxic conditions, which suggests not all species of macroinvertebrates are tolerant of anoxic conditions.

For fish, the effects of oxygen deprivation are more severe. In the study of Thetmeyer et al. (1999), effects of deprived oxygen conditions on growth of European sea bass (*Dicentrarchus labrax L.*) were investigated and reduced growth was found under moderate hypoxic or oscillating oxygen conditions. Similar results were found by Chabot & Dutil (1999) for Atlantic cod (*Gadus morhua)*, by Buentello et al. (2000) for channel catfish (*Ictalurus punctatus*), by Dam & Pauly (1995) for Nile tilapia (*Oreochromis niloticus L.*) and by Pedersen (1987) for rainbow trout (*Salmo gairdneri)*.

A multiple regression analysis with the data collected during the fieldwork showed a significant (p<.05) negative correlation between duckweed coverage and oxygen availability in mg/L and a significant positive correlation between duckweed coverage and oxygen availability in % (see table 5 on page 24). The analysis shows an increase in duckweed coverage with 1% corresponds to a decrease in oxygen availability of 86.11 mg/L, with a 95% certainty range of -160.95 mg/L to -11.26 mg/L, which indicates a very strong negative correlation that is in alignment with literature. The analysis also shows an increase in duckweed coverage with 1% corresponds to an increase in oxygen availability of 7.70%, with a 95% certainty range of 0.67% to 14.73%. This indicates a positive correlation where literature suggested a negative correlation. This could be due to a third parameter that is not accounted for in this research.

A similar analysis is conducted with the data from the complete combined dataset. A significant (p<.05) negative correlation is found between duckweed coverage and oxygen availability in mg/L, which is in alignment with literature (see table 5 on page 24). The analysis showed that an increase in duckweed coverage with 1% corresponds to a decrease in oxygen availability of 1.11 mg/L, with a 95% certainty range of -0.87 mg/L to -1.36 mg/L. With the data from the combined dataset that is collected during the peak of the duckweed growth season, a significant (p<.05) negative correlation was found in which an increase in duckweed coverage with 1% corresponds to a decrease in oxygen availability of 2.11 mg/L, with a 95% certainty range of -0.40 mg/L to -3.83 mg/L. With the data from the combined dataset that contains a value for duckweed coverage different than 5%, a significant (p<.05) negative correlation was found in which an increase in duckweed coverage with 1% corresponds to a decrease in oxygen availability of 4.74 mg/L, with a 95% certainty range of -2.16 mg/L to -7.33 mg/L. The slope values for the correlation between duckweed coverage and oxygen availability in mg/L from all three selections of the combined dataset are low, indicating weak negative correlations, in alignment with literature. The correlation between duckweed coverage and oxygen availability in % was not significant in all three selections of the combined dataset (see table 5 on page 24).

An individual regression analysis with the data from the fieldwork showed a significant (p<.05) positive correlation between time of the day and oxygen availability, in which 33.9% of the variance in oxygen availability can be explained by the variance in time and an increase of time with one hour corresponds to an increase in oxygen availability of 1.31 mg/L or 13.8% (note: all fieldwork data was collected between 9AM and 4.30PM). A second regression analysis with the data from the combined dataset also showed a significant (p<.05) positive correlation between time of the day and oxygen availability, in which 31.2% of the variance in oxygen availability can be explained by the variance in time and an increase of time with one hour corresponds to an increase in oxygen availability of 7.89 mg/L or 74.6% (note: all data from the combined dataset was collected between 6.30AM and 6PM). However, standardizing the oxygen availability with the time and using this value in the multiple regression analyses instead of the unstandardized oxygen availability gave similar results in this research. Therefore, it is decided to neglect the influence of time on oxygen availability in this research.

The found correlation between duckweed and oxygen availability could be caused by high temperatures. High temperatures are causing low oxygen availability through an increase of microbial activity (Carvalho et al., 2005) and high temperatures also cause an increase in duckweed coverage (Oron & Willers, 1989; Wedge & Burris, 1982). Thus, duckweed coverage might not *cause* a decrease in oxygen availability but *correlate* to it because they are both influenced by temperature. This could explain observations in the field where oxygen deprivation took place before the start of duckweed growth.

3.2.2 (sun)Light penetration

The degree of available (sun)light at any given depth of a water column affects the rate of photosynthesis of the plants growing there and therefore the amount of oxygen available (see **3.2.1** *Oxygen availability*). A sufficient degree of (sun)light penetration is important for algae or submersed plants to grow (Queensland Government, 2018). Duckweed forms a floating surface on the water column, reducing the ability of the (sun)light to penetrate (figure 12). However, duckweed also decreases the turbidity of the water by reducing the influence of wind and the growth of algae, thereby improving the ability of the (sun)light to penetrate. In this research, (sun)light penetration is measured in terms of turbidity and not in terms of light intensity, so no conclusions can be drawn about reduced light intensity underneath duckweed coverage.

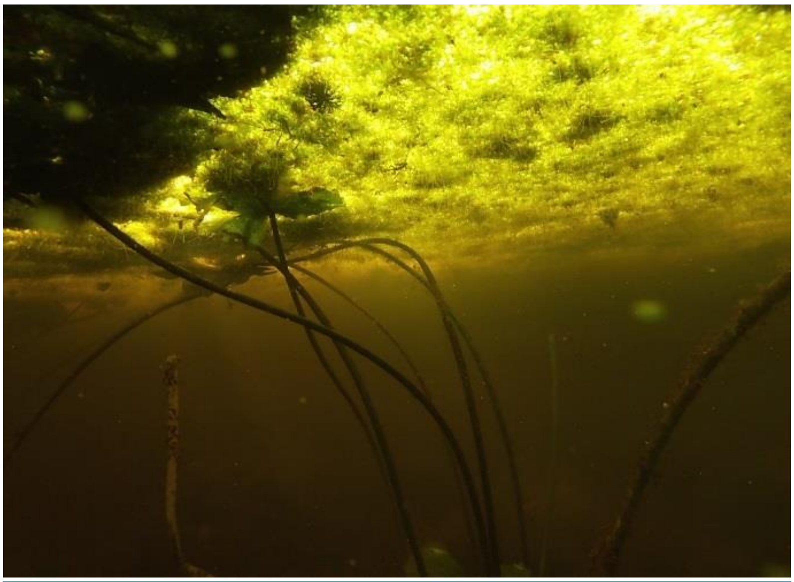

Figure 12: Reduced (sun)light penetration due to duckweed coverage.

For macrophytes, light is one of the most important limiting resources (Spence, 1982). In 1983, Kelly et al. researched the influence of light on primary productivity in a macrophyte-dominated river and found a remarkably constant relationship. Shading in the aquatic environment may be (apart from duckweed) caused by phytoplankton populations, suspended particulate matter in the water column, epiphytes, and other macrophytes (Farmer, 1990). The study of Janes et al. (1996) showed different species of submersed plants react differently to a decrease in available (sun)light. For example, pondweed is more negatively influenced than waterweed. In the study of Jones et al. (1983) decreased light penetration was correlated with extinction of the submersed macrophyte *Myriophyllum spicatum*. Cuassolo et al. (2016) studied two species of wetland plants (*Eleocharis pachycarpa* and *Potentilla anserina*) under differing light conditions and found the particulate organic matter as well as the dissolved organic matter to decrease significantly with decreasing available light ($p<.05$). The study of Luhtala et al. (2016) confirms the important role light availability has in regulating the macrophyte growth. In the studies of Zhu et al. (2018) and Huang et al. (2019), light intensity was found to mostly influence the toxic effects of ammonia and cadmium, thereby decreasing the growth of macrophytes *Vallisneria natans* and *Potamogeton crispus*, respectively.

Light availability was also appointed as a determining factor for the temporal variability of periphytic algae growth in the study of Santos & Ferragut (2018). The study of Brady (2019) suggested a positive correlation between light availability and the activity of macroinvertebrates. In the study of Guo et al. (2016), it was shown that shading caused a decrease in algal polyunsaturated fatty acids, which are essential for somatic growth and reproduction of aquatic animals. The study of Martyniuk et al. (2019) confirmed light is a key factor for primary production and primary producer nutrient stoichiometry, and thereby affects macroinvertebrate grazers.

Shade and its effects on fish assemblages have been widely studied in streams throughout the world (e.g. Jones et al. 1999; Burcher et al. 2008; Broadmeadow et al. 2011; Pusey and Arthington 2003). Fish have been observed to reduce their activity levels in shaded areas (Block et al. 1984). Jones et al. (1999) found an overall decrease in fish abundance with increasing length of reach with non-shaded areas. On the other hand, inability to obtain thermal refuge and reduce activity can directly or indirectly result in fish mortality (Plumb and Hanson 2011). In some studies, the overall species richness (gamma diversity) was higher in shaded sites (Raines & Miranda, 2016). Results of the study by Burcher et al. (1999) suggest that the diversity and/or richness in fish species may be lower in streams having less shade compared to streams having more shade.

The data collected during the fieldwork showed no significant correlation between duckweed coverage and (sun)light penetration (see table 5 on page 24). A multiple regression analysis with the data from the complete combined dataset showed a significant ($p<.05$) negative correlation between duckweed coverage and (sun)light penetration. In this correlation, an increase of duckweed coverage with 1% relates to a decrease in (sun)light penetration of 0.03 centimeters, with a 95% certainty range of -0.02 cm to -0.04 cm. With the data from the combined dataset that is collected during the peak of the duckweed growth season, a significant ($p<.05$) negative correlation was found between duckweed coverage and (sun)light penetration in which an increase of duckweed coverage with 1% relates to a decrease in (sun)light penetration of 0.04 centimeters, with a 95% certainty range of -0.02 cm to -0.07 cm. With the data from the combined dataset that contains a value for duckweed coverage different than 5%, a significant ($p<.05$) negative correlation was found in which an increase in duckweed coverage with 1% corresponds to a decrease in (sun)light penetration of 0.20 centimeters, with a 95% certainty range of -0.13 cm to -0.27 cm. These values are all very low, indicating a weak negative correlation between duckweed coverage and (sun)light penetration, which is in alignment with literature.

3.2.3 Electrical Conductivity

Electrical conductivity (EC) is a measure of the ability to conduct an electrical current (Queensland Government, 2018). The electrical conductivity of water is a quick measure of its total dissolved salt concentration; an increase in EC implies a slight increase in salinity (Oster & Rhoades, 2018). EC varies with temperature; a difference of 5°C can alter conductivity by approximately 10% (Queensland Government, 2018). Therefore, EC values are usually corrected to 25°C, known as specific conductance or EC_{25}. Specific conductance can be calculated by using the formula:

$$EC_{25} = \frac{EC_t}{1+0.019\,(t-25)} \qquad \text{F1}$$

In this formula, EC_{25} = Specific conductance in µS/cm (EC corrected to 25°C), EC_t = EC at the measured temperature in µS/cm, t = water temperature in °C where and when EC is measured (Queensland Government, 2018). The EC values found during the fieldwork of this research are converted into specific conductance values by using this formula.

Chemically pure water does not conduct electricity. Rainwater typically has an EC value below 600 µg/L (Ogren et al., 1983), which corresponds to about 1 µS/cm (assuming a density of water of 1.00 g/mL). Any rise in the electrical conductivity of water indicates the presence of higher amount of dissolved inorganic substances in ionized form and thus pollution (Tiwari et al., 2016).

In the study of Wendeou et al. (2013), the optimum range for duckweeds growth was found to be between conductivities of 600 µS/cm and 1400 µS/cm. The maximum growth rate was found at a conductivity of 1200 µS/cm. EC values above 2000 µS/cm reflected conditions with conductivity being a growth limiting factors. In the same study, the increase in EC was associated with an increase in duckweed biomass. The empirical study of Iqbal et al. (2017) also indicated a significant correlation between EC and biomass production of duckweed, with duckweed growing well at an EC range of 500-1500 µS/cm under natural climatic conditions and maximum duckweed growth observed at 1000 µS/cm.

The empirical study of Crossley et al. (2002) correlated the growth of the submerged aquatic macrophyte species *Aponogeton elongatus* with an increase in EC. The study of Chatenet et al. (2006) showed similar results, correlating an increase in stem diameter of the aquatic plant *Myriophyllum alterniflorum* to an increase in EC. A positive correlation with EC was also found in the study of Sager & Clerc (2006) on the occurrence of the microphyte water dock (*Rumex hydrolapathum*). In contrast, the empirical study of Carvalho et al. (2005) monitored the decomposition rate of submerged macrophytes for 55 days and found an increase in EC, which can be attributed to an increase of microbial activity.

For macroinvertebrates, an increase in EC was reported to be one the most important stressors apart from vegetation loss (Kath et al., 2018; Kefford & Robley, 1996). In the study of McLean et al. (2016), it was found that aquatic-macroinvertebrate community structure was influenced by EC through a complex combination of direct and indirect relationships, for example through predator occurrence and abundance. Chawaka et al. (2018) found a negative correlation between EC and the abundance of macroinvertebrates, which is in alignment with the results of Kefford (1998) and Kefford & Robley (1996), who also reported decreasing abundances of macroinvertebrates at higher electrical conductivities.

Environments of stable salinity, such as freshwater streams, are usually inhabited by stenohaline fish species, having narrow salinity tolerance ranges (Kültz, 2015). An increase in EC could therefore cause migration of these species to less saline waters (Gutierre et al., 2016). In the study of Özdemir et al. (2015), ecological requirements and distribution of the native and non-native freshwater fish species of the Muğla Province were studied between 2009 and 2011. In total, 19 fish species including 5432 specimens were collected from 17 water bodies. It was found that altitude, electrical conductivity and water temperature were the three most influential variables with respect to species occurrence ($p<.05$). The average estimated species optimum for EC in the study of Özdemir et al. (2015) was 508 µS/cm, with an average tolerance of 123 µS/cm.

Based on literature, EC has both positive and negative effects on the EWQ. A regression analysis was conducted with the data collected during the fieldwork as well as with the data from the combined dataset (see table 5 on page 24). Both analyses indicated no significant correlation between duckweed coverage and specific conductance ($p<.05$). With the data from the combined dataset that contains a value for duckweed coverage different than 5% and with the data from the combined dataset that is collected during the peak of the duckweed growth season, also no significant correlations were found.

3.3 Ecological water quality

The Impacts in a DPSIR framework are often stated in terms of measurable damages to the environment or human health (Ness et al., 2010). In this research, the Impact is defined as the ecological water quality in terms of macrophytes, macroinvertebrates and fish. The occurrence of macrophytes is strongly related to the abiotic conditions and therefore highly appropriate as an indicator for the EWQ (STOWA, 2010). Macroinvertebrates play an important role in the decomposition of organic materials, which is an important motive to use macroinvertebrates as an indicator for the EWQ (STOWA, 2010). Other sources are also using macroinvertebrates and fish in the assessment of EWQ; for example in Noord-Brabant by Doeser et al. (1991) and in Drenthe by Duursema & Torenbeek (1997). The basic assumption is the correlation between rare species and the EWQ (Nijboer, 2006). Especially species with a small environmental amplitude (low tolerance for environmental factors as substrate, current, vegetation structure, oxygen availability and food supply) are interesting for the assessment of EWQ (STOWA, 2010). Apart from environmental factors, factors as predation can have a significant influence on the abundance of those species. Floating plants like duckweed provide a particularly valuable habitat for aquatic macroinvertebrates (Meutter et al., 2008), providing complex submerged habitats among their suspended root masses (Barker et al., 2014).

Because oxygen deprivation is an often-discussed effect of duckweed coverage, the water board of Delfland attempted to quantify this effect by determining a minimal value at which the oxygen concentration has negative effects on the EWQ in terms of fish, macrophytes and macroinvertebrates. This was done by surveying sixteen ecologists with expert knowledge. The results from this survey showed an assumed negative influence of oxygen deprivation after three months for a concentration below 5 mg/L and after one week for a concentration below 3 mg/L (Raaphorst, 2019a). For (sun)light penetration and EC, no minimal value could be determined at which negative effects act on the EWQ in terms of fish, macrophytes and macroinvertebrates.

From the data collected during the fieldwork, an individual regression analyses was conducted to find a correlation between duckweed coverage and submersed vegetation (macrophytes). However, no significant correlation was found. In the combined dataset, submersed vegetation was not recorded, therefore no regression analysis could be conducted with this dataset. Macroinvertebrates and fish were not recorded in the fieldwork nor in the combined dataset, therefore no regression analyses could be conducted. The correlations between the state parameters oxygen availability, (sun)light penetration and EC and the EWQ in terms of macrophytes, macroinvertebrates and fish could thus not be quantified. However, these correlations are described in literature, as can be read in the corresponding paragraphs 3.2.1 *Oxygen availability*, 3.2.2 *(sun)Light penetration* and 3.2.3 *Electrical Conductivity*. The correlations as described in literature are summarized in table 6 in 3.2 *State parameters*.

Duckweed coverage is negatively correlated to oxygen availability and (sun)light penetration ($p<.05$) and oxygen availability and (sun)light penetration are positively correlated to the EWQ. Therefore, the correlation between duckweed coverage and the EWQ in terms of oxygen availability and (sun)light penetration can be assumed to be negative. The correlation in terms of EC is more complicated as the correlation between duckweed coverage and EC is not confirmed by the data used in this research and the correlation between EC and the EWQ varies per species.

4. Duckweed in the HEV-network

Filamentous algae and floating algae beds were not found in any of the six locations during the fieldwork period and are therefore left out of the analysis. In the following paragraphs, the duckweed coverage and parameter values found for each location will be summarized. A table with the full fieldwork results is shown in appendix I. The values for duckweed coverage that were found during the fieldwork are visualized in appendix II. An overview of the current- and over time problem locations is provided in table 7.

Table 7: Overview of current problem locations and problem locations over time and their influence on the estimated ecological water quality.

Location	Current state	Over time	Estimated EWQ caused by duckweed coverage
Kwekerijweg the Hague	1: Problem area 2: No problem area 3: Problem area	1: Problem area 2: No problem area 3: Problem area	Degraded
Broeksloot Voorburg	1: No problem area 2: No problem area 3: Problem area	1: No problem area 2: No problem area 3: No problem area	Not degraded
Rodenrijseweg Berkel	1: Problem area 2: No problem area 3: No problem area	1: No problem area 2: No problem area 3: No problem area	Not degraded
Karikaatmolensloot Delft	1: No problem area 2: No problem area 3: No problem area	1: No problem area 2: No problem area 3: No problem area	Not degraded
Delft city center	1: No problem area 2: Problem area 3: Problem area	1: No problem area 2: Problem area 3: No problem area	Degraded
Polderweg Schiedam	1: No problem area 2: Problem area 3: No problem area	1: Problem area 2: Problem area 3: No problem area	Degraded

4.1 Current state

To estimate the current state of duckweed coverage in the HEV-network, six potential problem areas are monitored over the course of four weeks (see 2.1.1 *Fieldwork*). In the following paragraphs, the invariable characteristics of each area are shown, together with a map of its exact measurement locations and a table showing the found values for (duckweed) coverage and oxygen availability in that area.

An assessment is made on whether or not each location is considered a duckweed-related problem area, based on the minimal values (≥50% duckweed coverage for two or more consecutive weeks, ≥75% duckweed coverage for more than one week and/or ≤3 mg/L oxygen availability for more than one week, see 3.3 *Ecological water quality*) at which negative effects on the EWQ are expected according to the expert survey conducted by the water board of Delfland (Raaphorst, 2019a). Results exceeding 75% coverage or subceeding 3 mg/L oxygen availability are highlighted in red.

4.1.1 Kwekerijweg the Hague

Kwekerijweg the Hague		Measurement location 1	Measurement location 2	Measurement location 3
X coordinate	-	4,3053609	4,3029117	4,3072518
Y coordinate	-	52,1024705	52,1002599	52,1052762
Emers	%	3	4	4
Connectivity	1 to 3	2	2	2
Sludge depth	cm	15,00	5,00	6,00
Water depth	cm	55,00	82,50	60,00
Sludge ratio	%	22,46	5,95	9,09
Optimal wind direction 1	-	NE	NE	NNW
Optimal wind direction 2	-	SW	SW	SSE

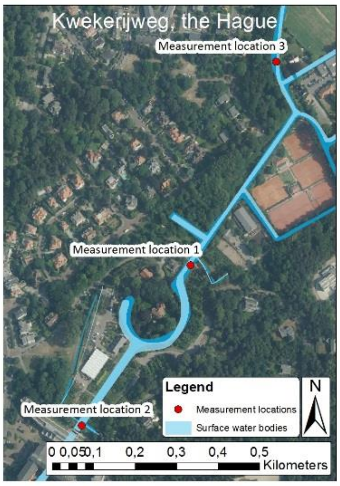

Table 8 (above): Characteristics of the measurement locations in this area.
Figure 13 (right): Map showing the measurement locations in this area.
Table 9 (below): Values found for coverage and oxygen availability at the measurement locations in this area.

Kwekerijweg the Hague			Measurement location 1				Measurement location 2				Measurement location 3			
Date		-	09-10-19	09-17-19	09-23-19	10-01-19	09-10-19	09-17-19	09-23-19	10-01-19	09-10-19	09-17-19	09-23-19	10-01-19
Time		-	11:13	11:50	9:50	11:00	11:50	12:15	10:00	11:10	11:58	12:20	10:25	11:30
Coverage	Total	%	95	35	100	100	82	55	5	5	100	100	100	100
	Duckweed	%	93	35	100	100	80	55	5	5	100	100	100	100
	Water fern	%	0	0	0	0	0	0	0	0	0	0	0	0
	Nymphaeaceae	%	2	0	0	0	2	0	0	0	0	0	0	0
Oxygen availability		mg/L	0,60	2,56	2,71	1,83	1,09	3,23	5,53	3,05	0,25	2,47	0,36	1,42
		%	5,7	25,4	27,7	18,7	10,7	32,3	56,4	31	2,5	24,5	3,6	14,7

In the area Kwekerijweg the Hague (table 8 and 9 and figure 13), the three measurement locations differed from each other quite a lot. Measurement locations one and especially two seemed to be more influenced by wind and/or current than measurement location three, which had a coverage of 100% during the entire fieldwork period. Measurement locations one and three had a duckweed cover of >75% for more than two weeks within the fieldwork period and are therefore assumed to have a negative influence on the EWQ. Besides, the oxygen concentration in these locations was <3 mg/L during all four weeks. Measurement location 2 had a duckweed coverage of >75% in the first week, but <75% in the other three weeks. The oxygen concentration in this location was <3 mg/L in the first week, <5 mg/L in the second and fourth week and >5 mg/L in the third week. Based on the fieldwork results on measurement locations one and three, the area Kwekerijweg the Hague is considered a current duckweed-related problem area.

4.1.2 Broeksloot Voorburg

In the area Broeksloot Voorburg (table 10 and 11 and figure 14 on the next page), each measurement location has a different orientation and thus a different optimal wind direction. A duckweed coverage of >75% was present on measurement location one in the third week and on measurement location three in the first and second week. An oxygen availability of <3 mg/L was observed in the second and fourth week on measurement location three, while it was <5 mg/L in all measurements except the first and second week on measurement location one and two. Based on the fieldwork results, measurement locations one and two of the area Broeksloot Voorburg are not considered current duckweed-related problem areas. Measurement location 3 is considered a current problem area.

4.1.3 Rodenrijseweg Berkel

In the area Rodenrijseweg Berkel (table 12 and 13 and figure 15 on the next page), the three measurement locations were alike in terms of connectivity and orientation. However the duckweed coverage varied. A duckweed coverage of >75% was present on measurement location one in the first, third and fourth week and on measurement location two in the second and third week. An oxygen availability of <3 mg/L was observed on measurement location one in the first and third week. An oxygen availability of <5 mg/L was observed on measurement location two in the third and fourth week. Based on the fieldwork results, measurement location one of the area Rodenrijseweg Berkel is considered a current duckweed-related problem area.

Broeksloot Voorburg		Measurement location 1	Measurement location 2	Measurement location 3
X coordinate	-	4,3772592	4,3729975	4,3633400
Y coordinate	-	52,0808076	52,0779930	52,0731160
Emers	%	5	0	0
Connectivity	1 to 3	3	3	2
Sludge depth	cm	10	5	2
Water depth	cm	80	80	90
Sludge ratio	%	10,54545455	5,882352941	2,173913043
Optimal wind direction 1	-	NE	NNE	NW
Optimal wind direction 2	-	SW	SSW	-

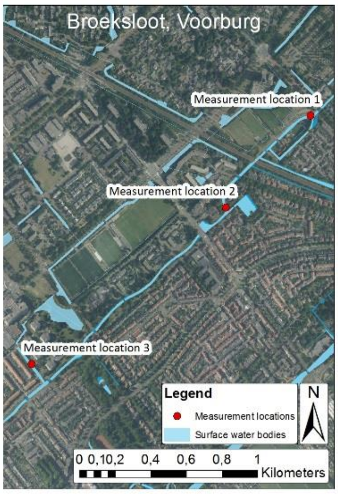

Table 10 (above): Characteristics of the measurement locations in this area.
Figure 14 (right): Map showing the measurement locations in this area.
Table 11 (below): Values found for coverage and oxygen availability at the measurement locations in this area.

Broeksloot Voorburg			Measurement location 1				Measurement location 2				Measurement location 3			
Date		-	09-10-19	09-17-19	09-23-19	10-01-19	09-10-19	09-17-19	09-23-19	10-01-19	09-10-19	09-17-19	09-23-19	10-01-19
Time		-	12:38	13:00	10:55	12:00	13:03	13:05	11:15	12:05	13:48	13:20	11:30	12:10
Coverage	Total	%	55	10	90	10	40	1	5	2	95	90	12	70
	Duckweed	%	55	10	90	10	40	1	5	2	90	85	7	60
	Water fern	%	0	0	0	0	0	0	0	0	0	0	0	5
	Nymphaeaceae	%	0	0	0	0	0	0	0	0	5	5	5	5
Oxygen availability		mg/L	8,14	6,24	4,83	3,47	7,99	6,48	4,36	3,85	4,38	2,56	4,43	1,34
		%	84	63,1	49,4	35,7	82,1	66,4	45	39,5	44,8	26	45,5	13,7

Polder Berkel		Measurement location 1	Measurement location 2	Measurement location 3
X coordinate	-	4,4630154	4,4699053	4,4539418
Y coordinate	-	51,9791236	51,9840825	51,9740788
Emers	%	0	3	4
Connectivity	1 to 3	3	3	3
Sludge depth	cm	3,50	50,00	30,00
Water depth	cm	82,50	90,00	100,00
Sludge ratio	%	3,87	35,90	23,08
Optimal wind direction 1	-	NE	NE	NNE
Optimal wind direction 2	-	SW	SW	SSW

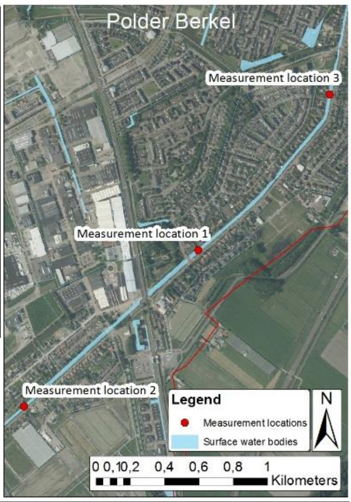

Table 12 (above): Characteristics of the measurement locations in this area.
Figure 15 (right): Map showing the measurement locations in this area.
Table 13 (below): Values found for coverage and oxygen availability at the measurement locations in this area.

Polder Berkel			Measurement location 1				Measurement location 2				Measurement location 3			
X coordinate			51,9791236				51,9840825				51,9740788			
Y coordinate			4,4630154				4,4699053				4,4539418			
Date		-	09-10-19	09-17-19	09-23-19	10-01-19	09-10-19	09-17-19	09-23-19	10-01-19	09-10-19	09-17-19	09-23-19	10-01-19
Time		-	14:39	14:00	13:00	12:55	15:12	14:10	13:15	12:50	15:25	14:30	12:45	13:05
Coverage	Total	%	90	45	100	95	62	77	95	52	15	10	10	15
	Duckweed	%	90	45	95	90	60	70	90	45	10	5	5	10
	Water fern	%	0	0	5	5	0	5	3	5	0	0	0	0
	Nymphaeaceae	%	0	0	0	0	2	2	2	2	5	5	5	5
Oxygen availability		mg/L	2,39	5,68	2,78	5,97	16,54	5,12	3,83	4,28	6,21	10,31	5,22	5,14
		%	25	59,2	28,7	61,9	177,8	53,5	40,3	44,2	65,4	108,1	55	53,1

4.1.4 Karikaatmolensloot Delft

In the area Karikaatmolensloot Delft (table 14 and 15 and figure 16 on the next page), a duckweed coverage of >75% was not found during the fieldwork. Oxygen values below 5 mg/L were also not found. Karikaatmolensloot is not considered a current duckweed-related problem area based on the fieldwork results.

Karikaatmolensloot Delft		Measurement location 1	Measurement location 2	Measurement location 3
X coordinate	-	4,4089605	4,3974166	4,3933300
Y coordinate	-	51,9897251	51,9878074	51,9896582
Emers	%	2	2	1
Connectivity	1 to 3	2	3	3
Sludge depth	cm	20,00	12,50	5,00
Water depth	cm	65,00	45,00	60,00
Sludge ratio	%	22,46	21,97	8,50
Optimal wind direction 1	-	ENE	ENE	NNW
Optimal wind direction 2	-	-	WSW	SSE

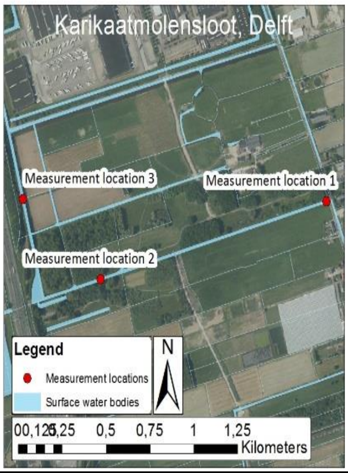

Table 14 (above): Characteristics of the measurement locations in this area.
Figure 16 (right): Map showing the measurement locations in this area.
Table 15 (below): Values found for coverage and oxygen availability at the measurement locations in this area.

Karikaatmolensloot Delft			Measurement location 1				Measurement location 2				Measurement location 3			
X coordinate			51,9897251				51,9878074				51,9896582			
Y coordinate			4,4089605				4,3974166				4,3933300			
Date		-	09-10-19	09-17-19	09-23-19	10-01-19	09-10-19	09-17-19	09-23-19	10-01-19	09-10-19	09-17-19	09-23-19	10-01-19
Time		-	15:50	14:50	12:45	13:20	16:07	15:00	12:10	13:35	16:25	15:10	11:50	13:40
Coverage	Total	%	40	2	1	10	55	30	55	10	16	1	1	2
	Duckweed	%	20	1	1	5	25	15	25	3	10	0	1	2
	Water fern	%	20	1	0	5	25	10	25	2	5	0	0	0
	Nymphaeaceae	%	0	0	0	0	5	5	5	5	1	1	0	0
Oxygen availability		mg/L	12,12	8,9	7,82	8,13	9,93	6,79	7,91	8,11	9,06	7,92	5,94	5,95
		%	126,6	93,2	83	84,7	103,5	71,3	83,6	84,5	93,5	82,5	62,7	61,9

4.1.5 City center Delft

In the city center of Delft (table 16 and 17 and figure 17), a total coverage of >75% was found on measurement location two in the first, second and third week and on measurement location three in all four weeks. However, the coverage with duckweed and water fern was only >75% in the first and second week on measurement location two and in the second and fourth week on measurement location three. The oxygen availability was <5 mg/L on all locations in all weeks and <3 mg/L on all locations except for measurement location one in the fourth week and measurement location two in the first week. Due to the low values of duckweed coverage in measurement location one, this location is not considered a duckweed-related problem area based on the fieldwork results, while measurement locations two and three are.

City centre Delft		Measurement location 1	Measurement location 2	Measurement location 3
X coordinate	-	4,3574893	4,3614636	4,3623897
Y coordinate	-	52,0145319	52,0132562	52,0106909
Emers	%	0	0	0
Connectivity	1 to 3	3	3	3
Sludge depth	cm	1,50	15,00	15,00
Water depth	cm	87,50	95,00	102,50
Sludge ratio	%	1,67	13,66	12,77
Optimal wind direction 1	-	NW	NE	NE
Optimal wind direction 2	-	SE	SW	SW

Table 16 (above): Characteristics of the measurement locations in this area.
Figure 17 (right): Map showing the measurement locations in this area.
Table 17 (below): Values found for coverage and oxygen availability at the measurement locations in this area.

City centre Delft			Measurement location 1				Measurement location 2				Measurement location 3			
X coordinate			52,0145319				52,0132562				52,0106909			
Y coordinate			4,3574893				4,3614636				4,3623897			
Date		-	09-12-19	09-19-19	09-26-19	10-03-19	09-12-19	09-19-19	09-26-19	10-03-19	09-12-19	09-19-19	09-26-19	10-03-19
Time		-	11:45	11:25	11:50	12:10	12:05	11:40	12:00	12:20	12:25	12:00	12:10	12:50
Coverage	Total	%	35	17	17	20	100	95	85	35	85	100	90	100
	Duckweed	%	20	2	2	5	85	80	70	20	30	40	40	40
	Water fern	%	0	0	0	0	0	0	0	5	35	40	30	40
	Nymphaeaceae	%	15	15	15	15	15	15	15	10	20	20	20	20
Oxygen availability		mg/L	1,98	1,56	1,87	3,38	4,43	0,24	1,24	2,43	2,53	1,2	0,17	0,34
		%	20,6	15,6	19,5	33,7	47,8	2,3	12,8	23,7	27	11,9	1,8	3,3

4.1.6 Polderweg Schiedam

In the area Polderweg Schiedam (table 18 and 19 and figure 18), there were some remarkable circumstances. Two floating booms were placed in the western end of the waterway; according to locals this was done to eliminate duckweed from the rest of the waterway. The first boom was situated about 50 meters east of measurement location one, the second boom was situated about 100 meters west of measurement location two. In week three and four, the second boom was lifted out of the water. Locals did this because they found ducklings struggling to get over the boom. The change was also visible in the duckweed coverage values, although this can also be attributed to other environmental factors. On measurement locations one and three, a lot of starwort was found. On average, starwort is more abundant at locations with low nutrient values than hornwort and western waterweed (STOWA, 2014). This could mean the nutrient value in de Polderweg is lower than in the other areas. On measurement location three, a quite high coverage of *Nymphaeceae* was found in comparison to the other areas, while (almost) no duckweed was detected during the fieldwork period.

A duckweed coverage of >75% was only observed in the first and second week on measurement location two. An oxygen availability of <5 mg/L was observed in the fourth week on measurement location one, in the second, third and fourth week on measurement location two and in all four weeks on measurement location three. Based on these observations, measurement location two of the area Polderweg Schiedam is considered a duckweed-related problem area. Measurement location three had low oxygen availability, but no duckweed coverage, so this location is not considered a duckweed-related problem area.

Polderweg Schiedam		Measurement location 1	Measurement location 2	Measurement location 3
X coordinate	-	4,3925729	4,3965546	4,4017608
Y coordinate	-	51,9423548	51,9393735	51,9361117
Emers	%	5	2	5
Connectivity	1 to 3	1	2	2
Sludge depth	cm	12,50	27,50	1,50
Water depth	cm	65,00	70,00	72,50
Sludge ratio	%	15,97	28,16	2,00
Optimal wind direction 1	-	NW	NW	NW
Optimal wind direction 2	-	-	SE	SE

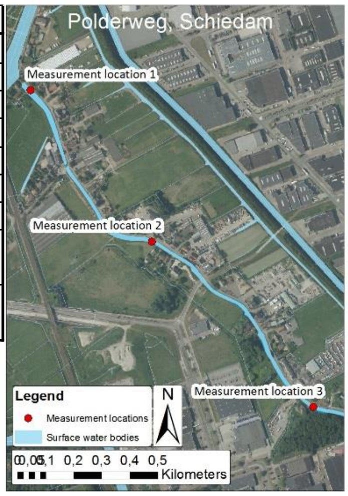

Table 18 (above): Characteristics of the measurement locations in this area.
Figure 18 (right): Map showing the measurement locations in this area.
Table 19 (below): Values found for coverage and oxygen availability at the measurement locations in this area.

Polderweg Schiedam			Measurement location 1				Measurement location 2				Measurement location 3			
Date		-	09-12-19	09-19-19	09-23-19	10-03-19	09-12-19	09-19-19	09-23-19	10-03-19	09-12-19	09-19-19	09-23-19	10-03-19
Time		-	14:17	13:50	14:10	13:35	14:47	14:10	13:55	13:50	15:30	14:30	13:45	14:05
Coverage	Total	%	65	55	45	45	92	92	40	52	40	40	40	41
	Duckweed	%	60	50	40	40	90	90	38	50	0	0	0	1
	Water fern	%	0	0	0	0	0	0	0	0	0	0	0	0
	Nymphaeaceae	%	5	5	5	5	2	2	2	2	40	40	40	40
Oxygen availability		mg/L	5,99	6,2	14,9	2,49	5,01	4,84	3,43	4,42	2,86	4,1	3,97	3,67
		%	65,2	63	160,7	24,6	53,6	48,7	35,9	42,3	30,2	41,8	41,8	35,9

4.2 Variance over time

Variance in duckweed coverage over time for the six potential problem areas is assessed by looking at Google Earth, which contains satellite images from the years 2006 – 2019, Google Streetview (2008-2019) and satellite images from the website "https://satellietdataportaal.nl/" (2017-2019). Furthermore, aerial photographs of the years 2003-2018 and infrared images from 2013-2018 are obtained from the shared portal of the water board of Delfland. The exact dates of the aerial photographs and infrared images are unknown; thus estimations are made. Possible (duckweed) coverage can be observed from all those sources for the six potential problem areas. Graphs are made per area to show coverage- and temperature variance over the years. In these graphs, the months July-September are marked as summer months as they represent the optimal growth season of duckweed. Measurement locations are marked as a problem location when at least 20% of the measurements contained a value for duckweed coverage of 75% or higher. The results of the assessment are discussed in the next paragraphs. In the graphs, coverages of 0% are presented as 0.5% to distinguish them from 'no data' values.

4.2.1 Kwekerijweg the Hague

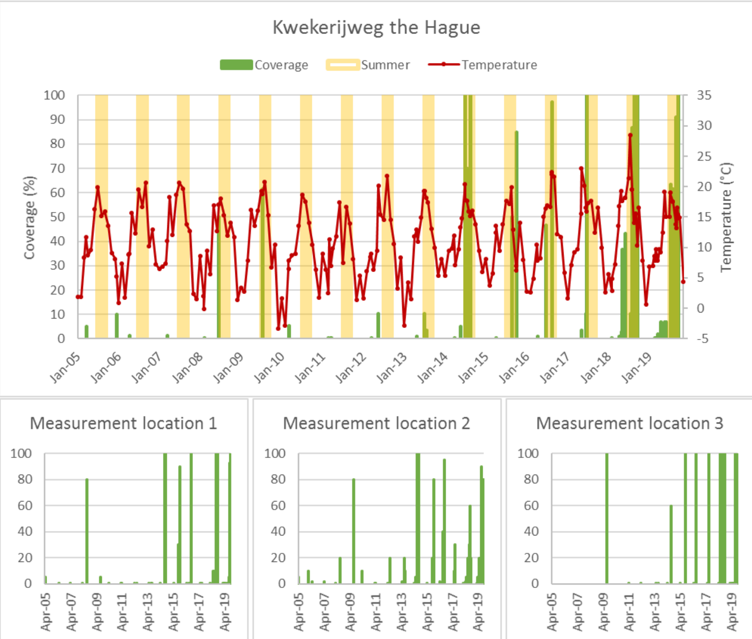

Figure 19: Average variance in duckweed coverage over time for the area Kwekerijweg the Hague (top) and variance in duckweed coverage over time for the three separate measurement locations (bottom).

Measurement location 3 of the area Kwekerijweg, the Hague was not visible on most Google Earth images due to overhanging trees. Measurement locations one and two were not accessible with Google Streetview. From the usable sources, all three measurement locations showed large amounts of duckweed in the summer months of 2014, 2015, 2016, 2018 and 2019. Measurement location one also showed a high value in June 2008, measurement location three showed a high value in July 2017 and measurement locations two and three showed a high value in July 2009. In the Kwekerijweg the Hague, 29.1% of the measurements contained a duckweed coverage value of 75% or higher. For measurement location one this was 25.5%, for measurement location two 17.6% and for measurement location three 50.0%.

The variation over time is visualized in figure 19. Based on the assessment of this variance over time, it can be stated that duckweed is a reoccurring problem in this area, especially in measurement locations one and two. The estimated EWQ for this area based on the duckweed coverage is degraded.

4.2.2 Broeksloot Voorburg

Measurement location one of the area Broeksloot Voorburg was not visible on Google Streetview. From the other sources, high amounts of duckweed were visible in the summer months of 2016, 2018 and 2019, just like in measurement location two and three. Measurement location two also showed high amounts of duckweed in July and August of 2014 and measurement location three showed a high amount in August 2015. In the Broeksloot Voorburg, 11.1% of the measurements contained a duckweed coverage value of 75% or higher. For measurement location one this was 6.0%, for measurement location two 14.0% and for measurement location three 12.7%.

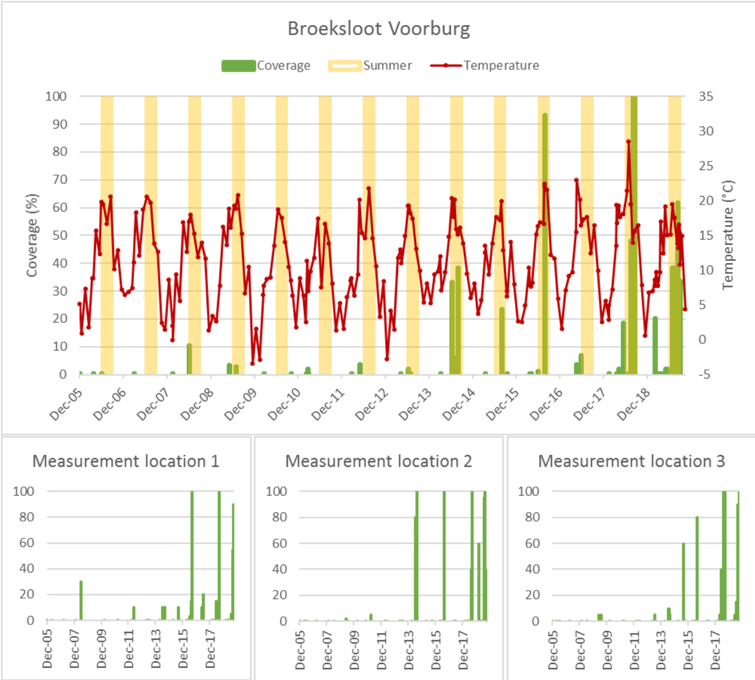

Figure 20: Average variance in duckweed coverage over time for the area Broeksloot Voorburg (top) and variance in duckweed coverage over time for the three separate measurement locations (bottom).

The variation in duckweed coverage over time is visualized in figure 20. Based on the assessment of this variance, Broeksloot Voorburg is not considered a problem area. The estimated EWQ for this area based on the duckweed coverage is not degraded.

4.2.3 Rodenrijseweg Berkel

The different sources show differing coverage values for the area Rodenrijseweg Berkel. On most images, duckweed coverage is medium (40-75%) or low (<40%). On some images, high values of duckweed coverage are visible (>75%), mostly in the latest images (2016-2019). The image of July 2014 showed a coverage of (almost) 100% on measurement locations 1 and 3 and a coverage of 50% on location 2. However, on the image of august 2014, the duckweed coverage was (close to) zero on all three locations. The same occurs in 2017 and 2018; a month with very high coverage is followed by (almost) zero coverage in the next month. This could be explained by the open connection; it is assumed that wind has a high influence in this area. Based on the rapid fluctuations, Rodenrijseweg Berkel does not appear to be a problem location, as duckweed does not stay on the same location for long periods of time.

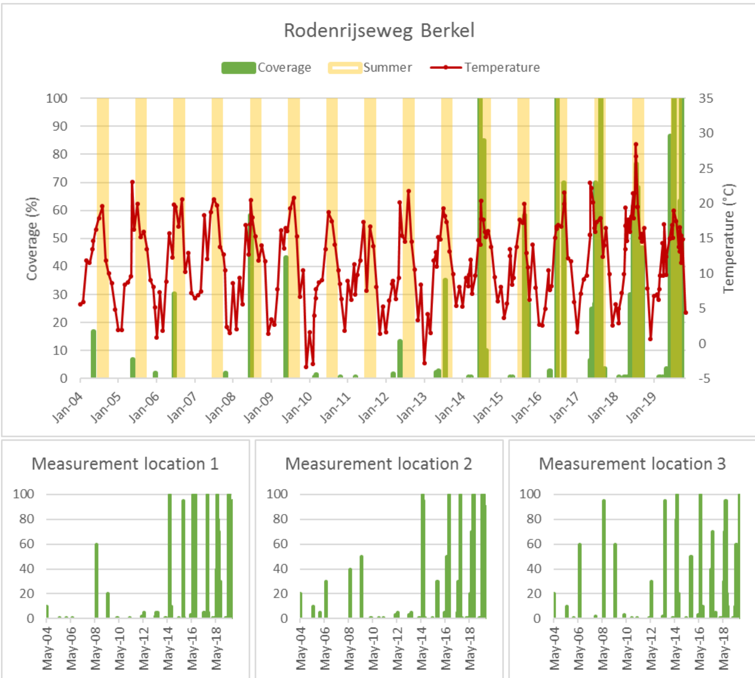

Figure 21: Average variance in duckweed coverage over time for the area Rodenrijseweg Berkel (top) and variance in duckweed coverage over time for the three separate measurement locations (bottom).

In the Rodenrijseweg Berkel, 16.3% of the measurements contained a duckweed coverage value of 75% or higher. For measurement location one this was 18.8%, for measurement location two 15.9% and for measurement location three 14.2%. The variation in duckweed coverage over time is visualized in figure 21. The estimated EWQ for this area based on the duckweed coverage is not degraded.

4.2.4 Karikaatmolensloot

Of the area Karikaatmolensloot Delft, measurement location two was not visible on Google Streetview. The sources all showed no problematic amounts of duckweed in most years. There was some duckweed visible in 2009, 2014, 2015 and 2016, but the high values were only present for a short period of time. For example, on the image from October 1st 2015, a lot of duckweed is visible in measurement location one and two, but on the image of October 11 the coverage is zero. The aerial photographs and infrared images provided by the water board of Delfland also showed no significant amounts of duckweed. In the Karikaatmolensloot, 6.7% of the measurements contained a duckweed coverage value of 75% or higher. For measurement location one this was 6.0%, for measurement location two 5.0% and for measurement location three 2.0%.

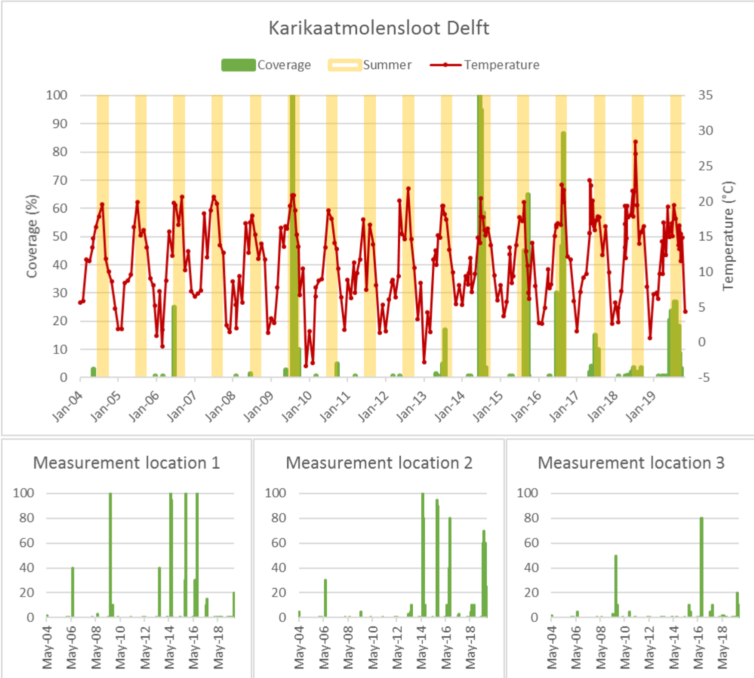

Figure 22: Average variance in duckweed coverage over time for the area Karikaatmolensloot Delft (top) and variance in duckweed coverage over time for the three separate measurement locations (bottom).

The variation in duckweed coverage over time is visualized in figure 22. Based on this variation, Karikaatmolensloot Delft is not considered a duckweed-related problem area. The estimated EWQ for this area based on the duckweed coverage is not degraded.

4.2.5 City center Delft

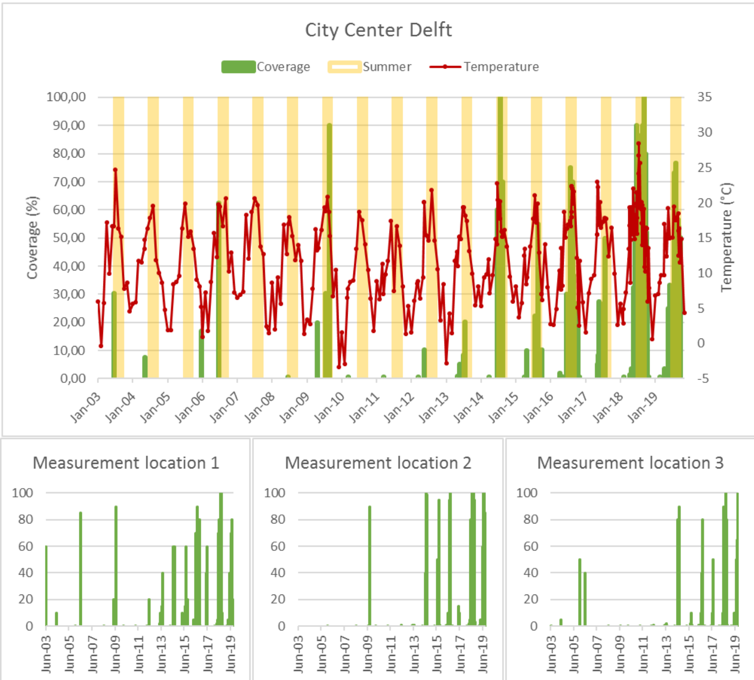

Figure 23: Average variance in duckweed coverage over time for the area City Center Delft (top) and variance in duckweed coverage over time for the three separate measurement locations (bottom).

For the city center of Delft, extra data points could be added by copying data from the dataset "Resultaten kroosmonitoring Delftse binnenstad"; it is assumed that data point 62 of the monitoring data corresponds to measurement location 1 of this research, data point 56 corresponds to measurement location 2 and data point 47 corresponds to measurement location 3.

In the city center of Delft, high percentages of duckweed coverage are found for the years 2009, 2014, 2016, 2018 and 2019. High coverage values mostly occur on two or more consecutive months. In the city center of Delft, 20.9% of the measurements contained a duckweed coverage value of 75% or higher. For measurement location one this was 16.7%, for measurement location two 35.6% and for measurement location three 11.3%. The variation in duckweed coverage over time is visualized in figure

23. Based on this variation, measurement location two of the city center of Delft is considered a problem area. The estimated EWQ for this area based on the duckweed coverage is medium.

4.2.6 Polderweg Schiedam

For the Polderweg Schiedam, extra data points could be added by copying data from an earlier study by Raaphorst (2019b). It is assumed that data point A003 of his research corresponds to measurement location 2 of this research and data point A001 corresponds to measurement location 3.

At the Polderweg Schiedam, large amounts of duckweed (>75%) are found on all three measurement locations in the years 2006, 2013, 2014, 2015, 2016 and 2018. Smaller amounts of duckweed (40-75%) are found in 2019. Remarkable in the area Polderweg Schiedam is the floating boom which is placed at the western end of the waterway. It is present in most years' images and creates a barrier between measurement location one and the rest of the waterway. Due to this boom, the duckweed coverage on measurement location one is almost always (close to) 100% or (close to) 0%.

In the Polderweg Schiedam, 22.0% of the measurements contained a duckweed coverage value of 75% or higher. For measurement location one this was 32.4%, for measurement location two 21.7% and for measurement location three 16.5%. The variation in duckweed coverage over time is visualized in figure 24. Based on this variation, Polderweg Schiedam is considered a problem area, especially measurement locations one and two. The estimated EWQ for this area based on the duckweed coverage is degraded.

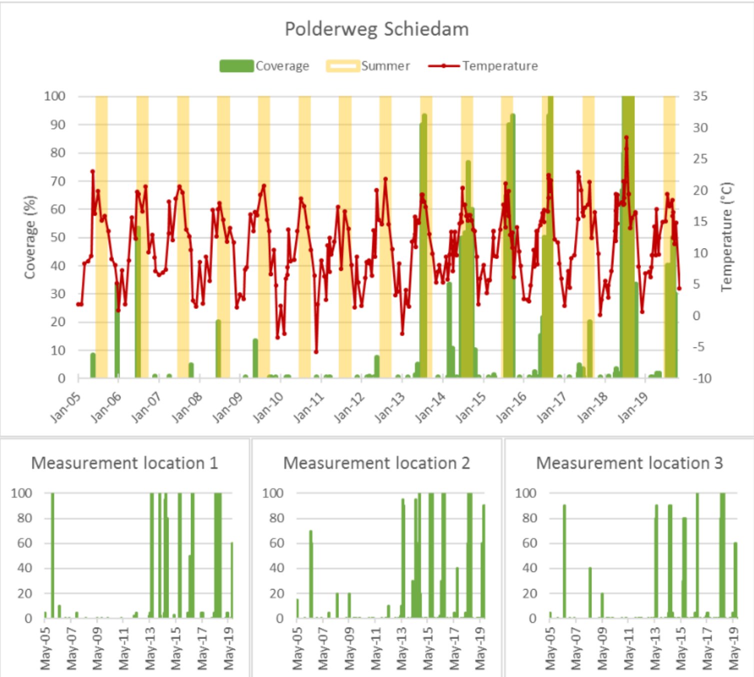

Figure 24: Average variance in duckweed coverage over time for the area Polderweg Schiedam (top) and variance in duckweed coverage over time for the three separate measurement locations (bottom).

4.3 Variance over space

Variance over space is assessed by looking at a map that was created as part of the research of Bezemer (2019), which represents duckweed-related problematic locations in Delfland based on reports by residents, fieldwork executed by Aquon in the years 2014-2018 (locations with >75% duckweed coverage), literature research and interviews with local operational water level managements (appendix III). This map was enhanced with data from the fieldwork executed for this research (as explained in **4.1** *Current state* & **4.2** *Variance over time*) problem locations obtained from infrared- and aerial photographs (as explained in **2.2** *Processing data*) and fieldwork executed by Aquon in 2019 (locations with >75% duckweed coverage). By looking at intersects between multiple problem locations, eleven duckweed-related problem areas are distinguished, of which eight are an intersect of two problem locations, one is an intersect of three problem locations and two are an intersect of more than three problem locations (figure 25). A detailed version of this map is included in appendix IV.

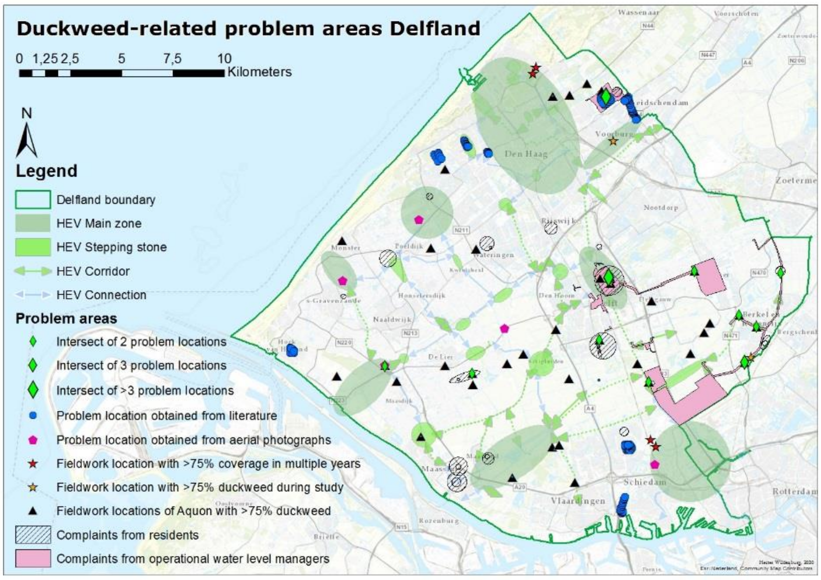

Figure 25: Duckweed-related problem areas Delfland

By comparing the situation of the problem locations to the HEV-network, it can be concluded that some problem locations are more severe than others. For example, from the two biggest problem areas (the green diamonds in Leidschendam and Delft), the southern one (Delft) is more severe since it is situated in a main zone of the HEV-network, whereas the northern one (Leidschendam) is not.

For the same reason, some of the intersects of problem locations are considered less severe than single problem locations that are situated in a HEV main zone. For example, the green diamonds in the eastern part of Delfland are considered less severe than the problem locations obtained from aerial photographs that are situated in the two north/western HEV main zones.

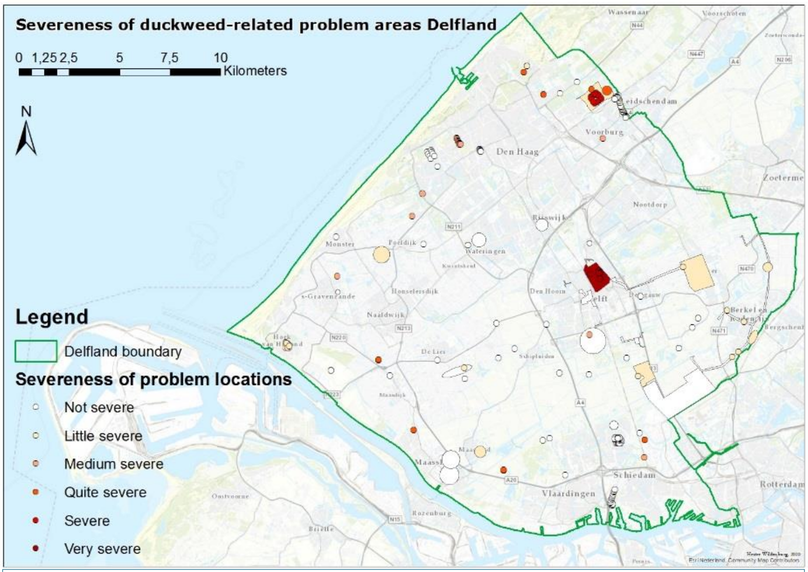

Figure 26: Severeness of duckweed-related problem areas Delfland, ranked from zero to five.

Based on this method of reasoning, a ranking system is created, which is shown in table 20. From this table, a map is created in which the problem locations are ranked from not severe (0) to very severe (5). This map is shown in figure 26 and in detail in appendix V.

Table 20: Ranking system for the severeness of duckweed-related problem areas, from not severe (0) to very severe (5)

Severeness of problem location	No HEV	HEV
No intersect	0	2
Intersect of 2	1	3
Intersect of 3	2	4
Intersect of >3	3	5

Discussion

Finding significant correlations in empirical research or empirical ecological files is complicated; the set assumptions (see 2.2 *Processing data*) are not always realistic for the natural environment and some parameters that were not considered may have had an influence on the found correlations (such as dominant species, shading by overhanging trees or other location-dependent variables). Some parameters may be correlated in such a strong way that they conceal the correlations of other parameters (such as pH and oxygen availability, which showed strong correlations in this research). On top of that, research with big datasets (such as this) often shows significant correlations that appear only due to the size of the data, not the nature of it (Calude & Longo, 2017). In such datasets, correlations can be found between 'random' data points, which implies most found correlations in those datasets are spurious. However, the selections of the dataset made in this research (see 2.2 *Processing data*) reduced the size of the dataset in such a way that it can be assumed the found correlations in this research are valid. Duckweed is significantly correlated to the driver parameters nitrogen, phosphorus, temperature, pH and movement by wind and the state parameters oxygen availability and (sun)light penetration.

The data collected during the fieldwork of this research showed no significant correlation between duckweed coverage and (sun)light penetration. However, it should be noted that during the fieldwork, most locations had bottom view, which means (sun)light can penetrate to the bottom. As light intensity was not measured, it is impossible to draw conclusions about the possible (sun)light penetration in those areas should the water depth be bigger. Thus a (significant) correlation between duckweed coverage and (sun)light penetration cannot be ruled out. The data from the combined dataset did show significant correlations between duckweed coverage and (sun)light penetration.

In the complete combined dataset, almost all values for duckweed coverage were 5%. This weakened all correlations. By eliminating these measurements (the third selection of the combined dataset, see 2.2 *Processing data*), the amount of data to analyze decreased strongly. To validate the found correlations, further research with more data points with duckweed coverage values higher than 5% is recommended.

It can be concluded from this research that the relation between duckweed coverage and the EWQ is very complex and variable. With the current knowledge, the impact of duckweed on the EWQ cannot be quantified. To accurately quantify the EWQ, duckweed coverage values cannot suffice and measurements of oxygen availability, (sun)light penetration and EC are needed, as well as measurements of macrophytes, macroinvertebrates and fish. The water board of Delfland attempted to estimate a minimal value at which duckweed coverage has negative effects on the EWQ in terms of fish, macrophytes and macro invertebrates. This was done by surveying sixteen ecologists with expert knowledge and experience. The results from this survey showed an assumed negative influence on EWQ after two weeks for a duckweed coverage above 50% and after a few days for a duckweed coverage above 75% (Raaphorst, 2019a).

The significant correlations between duckweed coverage and the state parameters found in this research are weak. The strength of the correlations between the state parameters and the EWQ is unknown. However, even if these correlations are strong, the resulting correlations between duckweed coverage and the EWQ parameters would be weak due to the weak correlations between duckweed coverage and the state parameters. Based on the direction of the correlations, duckweed does have a negative impact (irrespective of the strength) on the EWQ in terms of macrophytes, macroinvertebrates and fish through reduced oxygen availability and (sun)light penetration.

The results concerning EC are less unanimous. Literature states a positive correlation between duckweed coverage and EC, yet in this research, no significant correlation is found. The correlations between EC and the EWQ parameters as stated in literature are also variable in direction. The impact of duckweed on the EWQ in terms of macrophytes, macroinvertebrates and fish through EC is therefore still questionable. Over all, the correlation between duckweed coverage and the EWQ in terms of macrophytes, macroinvertebrates and fish can be concluded to be negative, yet small. Based on the results of this research, the values formulated by the water board of Delfland seem to slightly overestimate the negative effects of duckweed on the EWQ.

In the assessment of duckweed variance over time, five out of the eighteen measurement locations show to be a problem location. However, in recent years and in summer months more data is available than in earlier years and in winter months. It is therefore possible that some locations have been experiencing problematic duckweed coverages that are not accounted for in this research. Due to little data from winter/autumn/spring months, no conclusions can be drawn about the (onset of the) growth period of duckweed.

The fieldwork showed that within the HEV-network of Delfland, seven out of the eighteen measurement locations currently show to be a duckweed-related problem location. Over time, five out of the eighteen measurement locations show to be a problem location. The four measurement locations that show to be a problem location both in the current situation and over time are measurement location one and three of the are Kwekerijweg the Hague, measurement location two of the area City center Delft and measurement location two of the area Polderweg Schiedam. The estimated EWQ is degraded by duckweed coverage in those locations. However, for all other measurement locations the EWQ is not degraded by duckweed coverage. In short, four out of eighteen or 22.2% of the water bodies in HEV-network of Delfland have an estimated degraded EWQ caused by duckweed coverage. As the six measurement areas are viewed as the worst-case scenarios of the HEV-network, it is assumed that the EWQ is not (severly) degraded by duckweed coverage in the rest of the HEV-network. Based on the estimation of severeness of the duckweed-related problem areas, two areas are considered very severe duckweed related problem areas; the city center of Delft and Leidschendam.

From the combined dataset, 389 out of 10461 measurement locations (measurement locations that did not contain a value for duckweed coverage were neglected) or 3.72% of the measurement locations showed a duckweed coverage of >75% (presented in appendix VI). These locations have an estimated degraded EWQ caused by duckweed coverage. This means 96.28% of the measurement locations have a duckweed coverage lower than 75% and are not expected to have a degraded EWQ caused by duckweed coverage. Based on these values, it can be concluded that duckweed does not cause a problematic EWQ in most water bodies of Delfland. However, there are some locations that show to be problematic; Kwekerijweg the Hague, the city center of Delft, the Polderweg Schiedam and Leidschendam.

If a decrease in duckweed coverage is desired, further research is recommended on the effects of removing duckweed with different methods. The removal of a large biomass of duckweed could remove whole cohorts of macroinvertebrate populations, including endangered species (Carey et al., 2018). Therefore, removal of duckweed should not be implemented without understanding the effects on invertebrate species composition and life-cycles. A source-directed approach on the right locations is advised as a better way to decrease the negative effects of duckweed. Examples of source-directed measures are to reduce nutrient values, broaden and/or deepen ditches, time the moment of dredging with the growth cycle of duckweed and stimulate the growth of species that increase the EWQ. Further research on source-directed measures for duckweed decrease is recommended if a decrease in duckweed coverage is desired.

Conclusions

The found correlations in this research can be assumed to be valid. Duckweed is significantly correlated to the driver parameters nitrogen, phosphorus, temperature, pH and movement by wind and the state parameters oxygen availability and (sun)light penetration. The relation between duckweed coverage and the ecological water quality is very complex and variable. Through the state parameters, duckweed has a negative correlation to the ecological water quality. However, the correlations between duckweed coverage and the state parameters are weak, thus the negative influence of duckweed on the ecological water quality in terms of macrophytes, macroinvertebrates and fish is small. The values at which duckweed coverage has negative effects on the EWQ in terms of fish, macrophytes and macro invertebrates as formulated by the water board of Delfland seem to slightly overestimate the negative effects of duckweed on the EWQ.

Within the HEV-network of Delfland, seven out of the eighteen measurement locations currently show to be a duckweed-related problem location. Over time, five out of the eighteen measurement locations show to be a problem location. Four out of eighteen or 22.2% of the water bodies within the HEV-network of Delfland have an estimated degraded ecological water quality caused by duckweed coverage. As the six measurement areas are viewed as the worst-case scenarios of the HEV-network, it is assumed that the EWQ is not (severly) degraded by duckweed coverage in the rest of the HEV-network. Based on the estimation of severeness of the duckweed-related problem areas, two areas are considered very severe duckweed related problem areas; the city center of Delft and Leidschendam. From the combined dataset, 389 out of 10461 measurement locations (measurement locations that did not contain a value for duckweed coverage were neglected) or 3.72% of the measurement locations have an estimated degraded EWQ caused by duckweed coverage. Based on these values, it can be concluded that duckweed does not cause a problematic EWQ in most water bodies of Delfland. However, there are some locations that show to be problematic; Kwekerijweg the Hague, the city center of Delft, the Polderweg Schiedam and Leidschendam.

Recommendations

During this research, some questions were raised that could not be answered within the limited time and with the limited resources of this research. Therefore, there are some recommendations on further research. First of all, further research with more data points with duckweed coverage values higher than 5% is recommended to confirm the found correlations.

Second, to determine the values at which duckweed coverage has negative effects on the EWQ in terms of fish, macrophytes and macro invertebrates, a fieldwork setup is recommended in which multiple locations are monitored daily for at least two weeks. Several locations should be monitored, with at least one location containing a duckweed coverage of 0-50%, at least one location containing a duckweed coverage of 50-75% and at least one location containing a duckweed coverage of >75%. All locations should be monitored for at least two weeks, starting at the onset of duckweed growth in that location. Parameters that should be monitored are at least duckweed coverage, oxygen availability and presence of submerged macrophytes. It is recommended to also measure amounts of macroinvertebrates and fish and light intensity at different depths and/or (sun)light penetration.

Thirdly, the parameter maintenance was disregarded in this research as it produced no results as not enough data could be gathered. However, the effects of mowing on duckweed growth are very interesting; adjusting the moment of maintenance to the growth period of duckweed might have a big impact on duckweed coverage. It is therefore recommended to research these effects by comparing the duckweed coverage (and other parameters) on several locations before and after mowing.

The correlations between the driver parameters nitrogen and phosphorus availability, sludge depth and pH and duckweed coverage are recommended to study in a controlled environment (lab), even as the correlations between duckweed coverage and the state parameters oxygen availability and (sun)light penetration.

Lastly, if a decrease in duckweed coverage is still desired, further research is recommended on the use of source-directed measures and the effects of removing duckweed with different methods.

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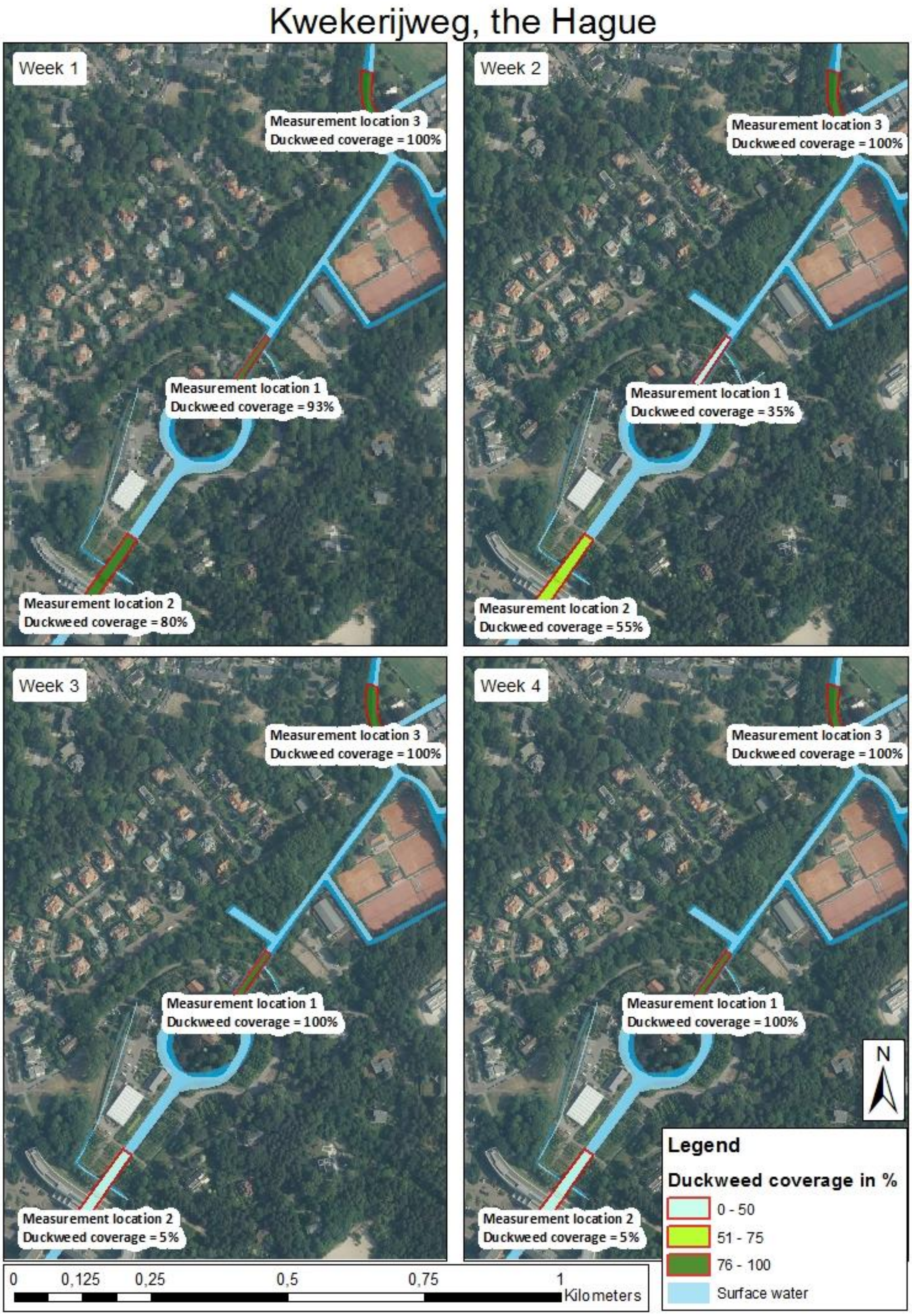
Appendices

Appendix I: Fieldwork results

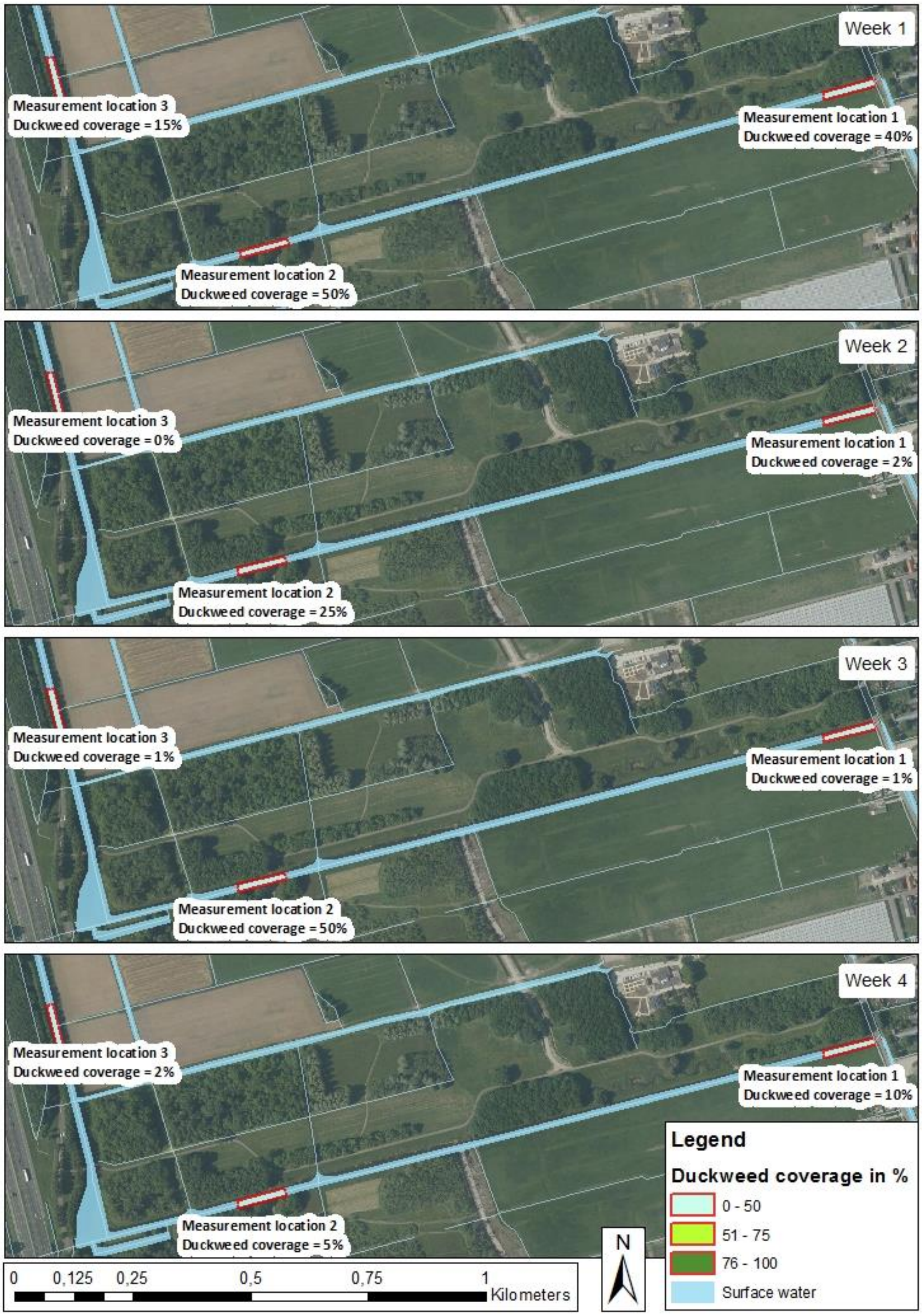
General								Driver								
		Optimal wind direction								Movement						
Location	Location code	1	2	X-coordinate	Y-coordinate	Date	Time	Emers	Temperature	Wind speed	Wind direction	Optimal	Influence of wind	By wind	Flow rate	Connectivity
-	-	-	-	-	-	-	-	%	℃	km/h	-	yes/no	0 to 3	0 to 5	0 to 3	0 to 3
Kwekerijweg Den Haag	1.1	NE	SW	52,1024705	4,3053609	09-10-19	11:13	3	14.0	6	SW	yes	0	0	0	2
		NE	SW	52,1024705	4,3053609	09-17-19	11:50	3	15.3	22	WNW	no	0	0	0	2
		NE	SW	52,1024705	4,3053609	09-23-19	9:50	3	16.3	12	SSW	no	0	0	0	2
		NE	SW	52,1024705	4,3053609	10-01-19	11:00	3	15.7	21	WSW	no	0	0	0	2
	1.2	NE	SW	52,1002599	4,3029117	09-10-19	11:50	4	14.7	5	SSW	no	0	0	0	2
		NE	SW	52,1002599	4,3029117	09-17-19	12:15	4	15.9	22	NW	no	0	0	0	2
		NE	SW	52,1002599	4,3029117	09-23-19	10:00	4	16.3	12	SSW	no	1	1	0	2
		NE	SW	52,1002599	4,3029117	10-01-19	11:10	4	15.6	12	WSW	no	1	1	0	2
	1.3	NNW	SSE	52,1052762	4,3072518	09-10-19	11:58	4	15.5	5	SW	no	0	0	0	2
		NNW	SSE	52,1052762	4,3072518	09-17-19	12:20	4	15.1	21	NW	no	0	0	0	2
		NNW	SSE	52,1052762	4,3072518	09-23-19	10:25	4	15.7	12	SSW	no	0	0	0	2
		NNW	SSE	52,1052762	4,3072518	10-01-19	11:30	4	16.9	19	WSW	no	0	0	0	2
Broeksloot Voorburg	2.1	NE	SW	52,0808076	4,3772592	09-10-19	12:38	5	17.1	5	SW	yes	0	0	1	3
		NE	SW	52,0808076	4,3772592	09-17-19	13:00	5	16.5	25	NW	no	1	2	0	3
		NE	SW	52,0808076	4,3772592	09-23-19	10:55	5	16.5	16	SSW	no	0	0	0	3
		NE	SW	52,0808076	4,3772592	10-01-19	12:00	5	16.1	21	WSW	no	2	3	0	3
	2.2	NNE	SSW	52,0779930	4,3729975	09-10-19	13:03	0	16.9	11	WSW	no	0	0	1	3
		NNE	SSW	52,0779930	4,3729975	09-17-19	13:05	0	17.0	27	NW	no	2	3	1	3
		NNE	SSW	52,0779930	4,3729975	09-23-19	11:15	0	16.9	18	S	no	1	1	2	3
		NNE	SSW	52,0779930	4,3729975	10-01-19	12:05	0	16.1	21	WSW	no	2	3	1	3
	2.3	NW	-	52,0731160	4,3633400	09-10-19	13:48	0	16.5	16	W	no	0	0	0	2
		NW	-	52,0731160	4,3633400	09-17-19	13:20	0	16.5	25	NNW	no	1	2	0	2
		NW	-	52,0731160	4,3633400	09-23-19	11:30	0	16.6	18	SSW	no	1	1	0	2
		NW	-	52,0731160	4,3633400	10-01-19	12:10	0	15.9	21	WSW	no	1	2	0	2
Polder Berkel	3.1	NE	SW	51,9791236	4,4630154	09-10-19	14:39	0	17.9	12	W	no	2	2	1	3
		NE	SW	51,9791236	4,4630154	09-17-19	14:00	0	17.7	19	NW	no	2	2	1	3
		NE	SW	51,9791236	4,4630154	09-23-19	13:00	0	16.9	19	SW	yes	0	0	0	3
		NE	SW	51,9791236	4,4630154	10-01-19	12:55	0	16.5	23	SW	yes	1	3	0	3
	3.2	NE	SW	51,9840825	4,4699053	09-10-19	15:12	3	19.1	11	WNW	no	1	1	2	3
		NE	SW	51,9840825	4,4699053	09-17-19	14:10	3	17.8	19	NW	no	1	1	0	3
		NE	SW	51,9840825	4,4699053	09-23-19	13:15	3	17.7	18	SW	yes	2	3	0	3
		NE	SW	51,9840825	4,4699053	10-01-19	12:50	3	16.2	25	SW	yes	2	4	0	3
	3.3	NNE	SSW	51,9740788	4,4539418	09-10-19	15:25	4	18.1	11	W	no	2	2	2	3
		NNE	SSW	51,9740788	4,4539418	09-17-19	14:30	4	18.1	22	NW	no	1	2	0	3
		NNE	SSW	51,9740788	4,4539418	09-23-19	12:45	4	17.9	17	SW	no	1	1	0	3
		NNE	SSW	51,9740788	4,4539418	10-01-19	13:05	4	16.2	22	SW	no	1	2	1	3
Karikaatmolensloot Delft	4.1	ENE	-	51,9897251	4,4089605	09-10-19	15:50	4	17.6	13	NW	no	1	1	0	2
		ENE	-	51,9897251	4,4089605	09-17-19	14:50	4	18.0	21	NW	no	1	2	1	2
		ENE	-	51,9897251	4,4089605	09-23-19	12:45	0	18.1	20	SSW	no	3	4	0	2
		ENE	-	51,9897251	4,4089605	10-01-19	13:20	0	16.6	22	SW	no	2	3	0	2
	4.2	ENE	WSW	51,9878074	4,3974166	09-10-19	16:07	2	17.6	11	W	no	0	0	1	3
		ENE	WSW	51,9878074	4,3974166	09-17-19	15:00	2	18.1	21	NW	no	0	0	0	3
		ENE	WSW	51,9878074	4,3974166	09-23-19	12:10	2	18.0	21	SW	no	0	0	1	3
		ENE	WSW	51,9878074	4,3974166	10-01-19	13:35	2	16.7	29	SW	no	1	2	1	3
	4.3	NNW	SSE	51,9896582	4,3933300	09-10-19	16:25	1	17.2	10	W	no	1	1	0	3
		NNW	SSE	51,9896582	4,3933300	09-17-19	15:10	1	17.7	24	NW	no	1	2	0	3
		NNW	SSE	51,9896582	4,3933300	09-23-19	11:50	1	17.9	21	SW	no	2	3	0	3
		NNW	SSE	51,9896582	4,3933300	10-01-19	13:40	1	16.6	25	SW	no	1	2	1	3
Delft city centre	5.1	NW	SE	52,0145319	4,3574893	09-12-19	11:45	0	17.9	19	WSW	no	1	1	1	3
		NW	SE	52,0145319	4,3574893	09-19-19	11:25	0	16.2	7	WNW	no	0	0	1	3
		NW	SE	52,0145319	4,3574893	09-26-19	11:50	0	16.6	25	S	no	2	3	1	3
		NW	SE	52,0145319	4,3574893	10-03-19	12:10	0	15.5	11	NW	yes	2	3	0	3
	5.2	NE	SW	52,0132562	4,3614636	09-12-19	12:05	0	19.5	18	WSW	no	0	0	0	3
		NE	SW	52,0132562	4,3614636	09-19-19	11:40	0	15.9	6	WNW	no	0	0	1	3
		NE	SW	52,0132562	4,3614636	09-26-19	12:00	0	16.2	25	S	no	0	0	1	3
		NE	SW	52,0132562	4,3614636	10-03-19	12:20	0	14.5	15	NW	no	1	1	1	3
	5.3	NE	SW	52,0106909	4,3623897	09-12-19	12:25	0	18.8	20	WSW	no	1	2	0	3
		NE	SW	52,0106909	4,3623897	09-19-19	12:00	0	15.6	6	NW	no	0	0	0	3
		NE	SW	52,0106909	4,3623897	09-26-19	12:10	0	15.8	26	SSW	no	1	2	0	3
		NE	SW	52,0106909	4,3623897	10-03-19	12:50	0	14.8	16	NNW	no	0	0	0	3
Polderweg Schiedam	6.1	NW	-	51,9423548	4,3925729	09-12-19	14:17	5	20.0	17	WSW	no	0	0	0	1
		NW	-	51,9423548	4,3925729	09-19-19	13:50	5	17.0	4	SSE	no	0	0	0	1
		NW	-	51,9423548	4,3925729	09-23-19	14:10	5	19.0	21	SW	no	0	0	0	1
		NW	-	51,9423548	4,3925729	10-03-19	13:35	5	15.0	7	W	no	0	0	0	1
	6.2	NW	SE	51,9393735	4,3965546	09-12-19	14:47	2	19.0	20	WSW	no	2	3	0	2
		NW	SE	51,9393735	4,3965546	09-19-19	14:10	2	16.7	4	NW	yes	0	0	0	2
		NW	SE	51,9393735	4,3965546	09-23-19	13:55	2	17.5	18	SW	no	1	1	1	2
		NW	SE	51,9393735	4,3965546	10-03-19	13:50	2	14.3	8	W	no	2	1	0	2
	6.3	NW	SE	51,9361117	4,4017608	09-12-19	15:30	5	18.5	21	WSW	no	1	2	0	2
		NW	SE	51,9361117	4,4017608	09-19-19	14:30	5	17.0	4	ENE	no	0	0	0	2
		NW	SE	51,9361117	4,4017608	09-23-19	13:45	5	17.9	18	SW	no	0	0	0	2
		NW	SE	51,9361117	4,4017608	10-03-19	14:05	5	14.6	13	WNW	no	1	1	0	2

Driver					Pressure				State								
Movement					Coverage							Conductivity			Attractiveness		
By current	Sludge depth	Water depth	Sludge ratio	pH	Total	Duckweed	Water fern	Nymphaeaceae	Submers	Oxygen availability		Electrical	Specific	Transparency	Odor	Color	Attractiveness
0 to 5	cm	cm	%	-	%	%	%	%	%	mg/L	%	µS/cm	µS/cm	cm / B	-	-	0 to 5
0	15	40	27,27	4,79	95	93	0	2	2	0,6	5,7	710	897,60	B	Neutral	Yellowish brown	2
0	15	40	27,27	11,78	35	35	0	0	2	2,56	25,4	740	907,20	B	Neutral	Yellowish brown	2
0	15	70	17,65	9,02	100	100	0	0	2	2,71	27,7	760	910,51	B	Neutral	Yellowish brown	2
0	15	70	17,65	7,09	100	100	0	0	2	1,83	18,7	699	849,02	B	Neutral	Yellowish brown	2
0	5	65	7,14	7,09	82	80	0	2	2	1,09	10,7	727	903,89	B	Neutral	Yellowish brown	2
0	5	65	7,14	9,04	55	55	0	0	2	3,23	32,3	781	944,26	B	Neutral	Yellowish brown	2
0	5	100	4,76	9,3	5	5	0	0	2	5,53	56,4	822	984,78	B	Neutral	Yellowish brown	2
0	5	100	4,76	7,43	5	5	0	0	2	3,05	31	731	889,94	B	Neutral	Yellowish brown	2
0	2	20	9,09	7,01	100	100	0	0	0	0,25	2,5	732	893,23	B	Mouldy	Yellowish brown	1
0	2	20	9,09	7,83	100	100	0	0	0	2,47	24,5	763	939,77	B	Mouldy	Yellowish brown	1
0	10	100	9,09	8,77	100	100	0	0	0	0,36	3,6	787	955,91	B	Mouldy	Brown	0
0	10	100	9,09	7,28	100	100	0	0	0	1,42	14,7	678	801,32	50	Mouldy	Brown	0
3	5	50	9,09	7,86	55	55	0	0	0	8,14	84	744	875,40	B	Neutral	Yellowish brown	2
0	5	50	9,09	7	10	10	0	0	0	6,24	63,1	750	894,45	B	Neutral	Yellowish brown	2
0	15	110	12,00	9,47	90	90	0	0	0	4,83	49,4	774	923,08	110	Neutral	Yellowish brown	2
0	15	110	12,00	7,73	10	10	0	0	0	3,47	35,7	662	796,73	B	Neutral	Yellowish brown	2
3	5	80	5,88	7,56	40	40	0	0	15	7,99	82,1	763	901,78	B	Neutral	Yellowish brown	2
3	5	80	5,88	9,2	1	1	0	0	15	6,48	66,4	795	937,50	B	Neutral	Yellowish brown	2
4	5	80	5,88	9,39	5	5	0	0	10	4,36	45	803	949,06	B	Neutral	Yellowish brown	2
3	5	80	5,88	7,82	2	2	0	0	10	3,85	39,5	734	883,38	B	Neutral	Yellowish brown	2
0	2	90	2,17	7,3	95	90	0	5	0	4,38	44,8	819	976,74	B	Neutral	Yellowish brown	2
0	2	90	2,17	-	90	85	0	5	0	2,56	26	798	951,70	B	Neutral	Yellowish brown	2
0	2	90	2,17	9,45	12	7	0	5	0	4,43	45,5	799	950,74	B	Neutral	Yellowish brown	2
0	2	90	2,17	8,07	70	60	5	5	0	1,34	13,7	745	900,74	B	Neutral	Yellowish brown	2
3	2	65	2,99	6,75	90	90	0	0	0	2,39	25	844	975,61	B	Neutral	Yellowish brown	2
3	2	65	2,99	9	45	45	0	0	0	5,68	59,2	851	988,04	B	Neutral	Yellowish brown	2
0	5	100	4,76	9,16	100	95	5	0	5	2,78	28,7	881	1041,25	B	Neutral	Yellowish brown	2
0	5	100	4,76	7,7	95	90	5	0	5	5,97	61,9	581	692,90	B	Neutral	Yellowish brown	2
4	50	80	38,46	8,01	62	60	0	2	15	16,54	177,8	865	974,21	70	Neutral	Brownrown	1
0	50	80	38,46	-	77	70	5	2	15	5,12	53,5	794	919,83	60	Neutral	Brownrown	1
0	50	100	33,33	9,32	95	90	3	2	15	3,83	40,3	822	954,37	B	Neutral	Yellowish brown	2
0	50	100	33,33	7,78	52	45	5	2	15	4,28	44,2	557	668,83	B	Neutral	Yellowish brown	2
4	30	100	23,08	6,96	15	10	0	5	10	6,21	65,4	861	990,91	60	Neutral	Brown	1
0	30	100	23,08	-	10	5	0	5	10	10,31	108,1	939	1080,68	70	Neutral	Brown	1
0	30	100	23,08	9,4	10	5	0	5	10	5,22	55	1037	1198,71	B	Neutral	Brown	1
3	30	100	23,08	7,76	15	10	0	5	10	5,14	53,1	645	774,50	B	Neutral	Yellowish brown	2
0	30	65	31,58	8,54	40	20	20	0	0	12,12	126,6	754	877,36	30	Neutral	Brown	1
2	30	65	31,58	-	2	1	1	0	0	8,9	93,2	763	880,05	50	Neutral	Brown	1
0	10	65	13,33	9,52	1	1	0	0	0	7,82	83	767	882,73	50	Neutral	Brown	1
0	10	65	13,33	8,07	10	5	5	0	0	8,13	84,7	633	753,21	40	Neutral	Brown	1
3	15	40	27,27	7,46	55	25	25	5	0	9,93	103,5	743	864,56	40	Neutral	Brown	1
0	15	40	27,27	-	30	15	10	5	0	6,79	71,3	768	883,88	40	Neutral	Brown	1
3	10	50	16,67	9,58	55	25	25	5	0	7,91	83,6	725	836,22	50	Neutral	Brown	1
3	10	50	16,67	8,05	10	3	2	5	0	8,11	84,5	694	823,93	40	Mouldy	Brown	0
0	5	40	11,11	7,25	16	10	5	1	0	9,06	93,5	705	827,66	40	Neutral	Brown	1
0	5	40	11,11	-	1	0	0	1	0	7,92	82,5	690	801,11	B	Neutral	Brown	1
0	5	80	5,88	9,49	1	1	0	0	0	5,94	62,7	738	853,08	70	Neutral	Brown	1
3	5	80	5,88	7,89	2	2	0	0	0	5,95	61,9	646	768,68	40	Neutral	Brown	1
3	1	85	1,16	-	35	20	0	15	5	1,98	20,6	738	853,08	B	Neutral	Yellowish brown	2
3	1	85	1,16	8,94	17	2	0	15	0	1,56	15,6	796	955,81	B	Neutral	Yellowish brown	2
3	2	90	2,17	7,51	17	2	0	15	0	1,87	19,5	762	906,71	B	Neutral	Yellowish brown	2
0	2	90	2,17	8,94	20	5	0	15	0	3,38	33,7	761	928,62	B	Neutral	Yellowish brown	2
0	15	100	13,04	-	100	85	0	15	40	4,43	47,8	744	830,82	70	Neutral	Yellowish brown	2
3	15	100	13,04	8,87	95	80	0	15	30	0,24	2,3	775	937,01	B	Neutral	Yellowish brown	2
3	15	90	14,29	7,48	85	70	0	15	40	1,24	12,8	708	850,14	B	Neutral	Yellowish brown	2
3	15	90	14,29	8,96	35	20	5	10	40	2,43	23,7	750	936,91	B	Neutral	Yellowish brown	2
0	15	105	12,50	-	85	30	35	20	40	2,53	27	687	778,73	100	Neutral	Yellowish brown	2
0	15	105	12,50	8,84	100	40	40	20	40	1,2	11,9	779	948,38	B	Neutral	Yellowish brown	2
0	15	100	13,04	7,41	90	40	30	20	30	0,17	1,8	770	933,11	B	Neutral	Yellowish brown	2
0	15	100	13,04	8,86	100	40	40	20	30	0,34	3,3	712	883,16	B	Neutral	Yellowish brown	2
0	10	60	14,29	8,28	65	60	0	5	90	5,99	65,2	860	950,28	20	Neutral	Brown	1
0	10	60	14,29	10,29	55	50	0	5	90	6,2	63	1128	1330,19	40	Neutral	Brown	1
0	15	70	17,65	10,29	45	40	0	5	90	14,9	160,7	1025	1156,88	30	Neutral	Brown	1
0	15	70	17,65	9,51	45	40	0	5	90	2,49	24,6	921	1137,04	30	Neutral	Brown	1
0	30	70	30,00	8,23	92	90	0	2	0	5,01	53,6	891	1005,64	70	Neutral	Brown	1
0	30	70	30,00	9,26	92	90	0	2	0	4,84	48,7	1010	1199,10	B	Neutral	Brown	1
2	25	70	26,32	9,27	40	38	0	2	0	3,43	35,9	1046	1219,83	B	Neutral	Yellowish brown	2
0	25	70	26,32	9,1	52	50	0	2	0	4,42	42,3	992	1245,14	B	Neutral	Yellowish brown	2
0	2	75	2,60	7,36	40	0	0	40	20	2,86	30,2	897	1023,39	B	Neutral	Brown	1
0	2	75	2,60	9,21	40	0	0	40	20	4,1	41,8	1005	1185,14	B	Neutral	Brown	1
0	1	70	1,41	9,3	40	0	0	40	20	3,97	41,8	1083	1251,88	B	Neutral	Yellowish brown	2
0	1	70	1,41	9,15	41	1	0	40	20	3,67	35,9	1037	1292,37	B	Neutral	Yellowish brown	2

Appendix II: Visualized duckweed coverage values



Karikaatmolensloot, Delft

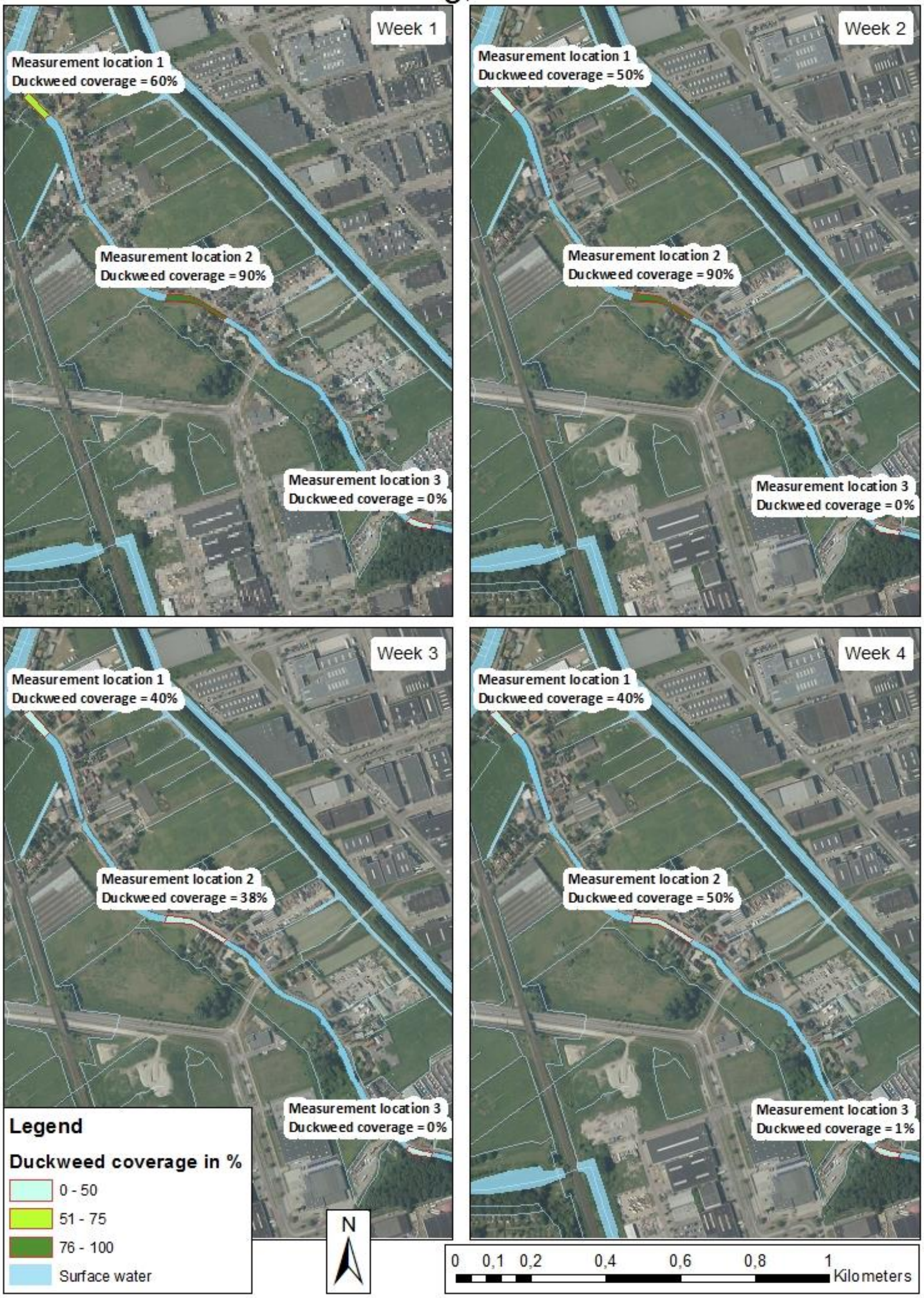


Broeksloot, Voorburg

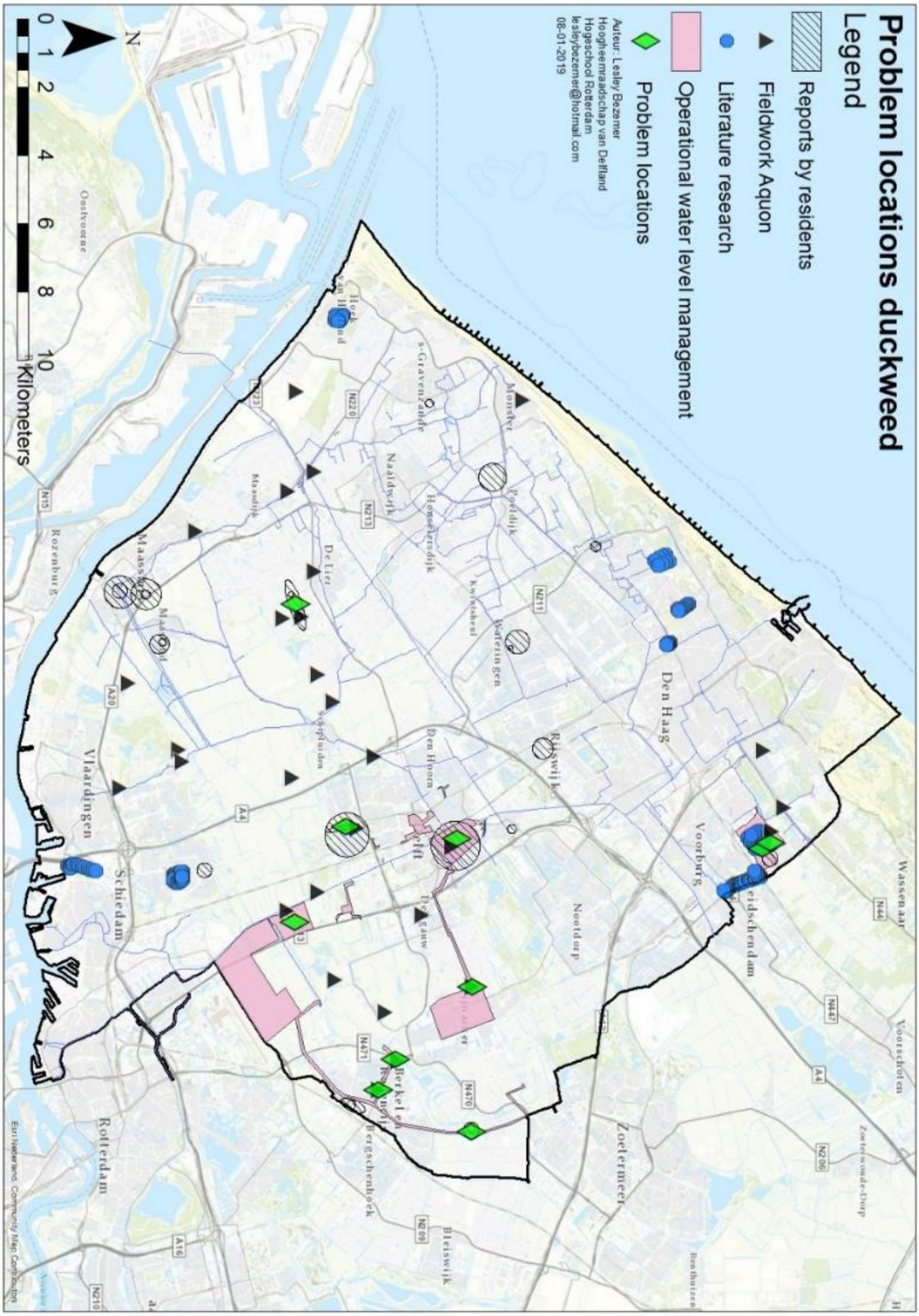
Polder Berkel


City centre Delft
Week 1
Measurement location 1
Duckweed coverage = 20%
Measurement location 2
Duckweed coverage = 85%
Measurement location 3
Duckweed coverage = 65%
Week 2
Measurement location 1
Duckweed coverage = 2%
Measurement location 2
Duckweed coverage = 80%
Measurement location 3
Duckweed coverage = 80%
Week 3
Measurement location 1
Duckweed coverage = 2%
Measurement location 2
Duckweed coverage = 70%
Measurement location 3
Duckweed coverage = 70%
Week 4
Measurement location 1
Duckweed coverage = 5%
Measurement location 2
Duckweed coverage = 25%
Measurement location 3
Duckweed coverage = 80%
Legend
Duckweed coverage in %
0 - 50
51 - 75
76 - 100
Surface water
N
0 0,075 0,15 0,3 0,45 0,6 0,75
Kilometers

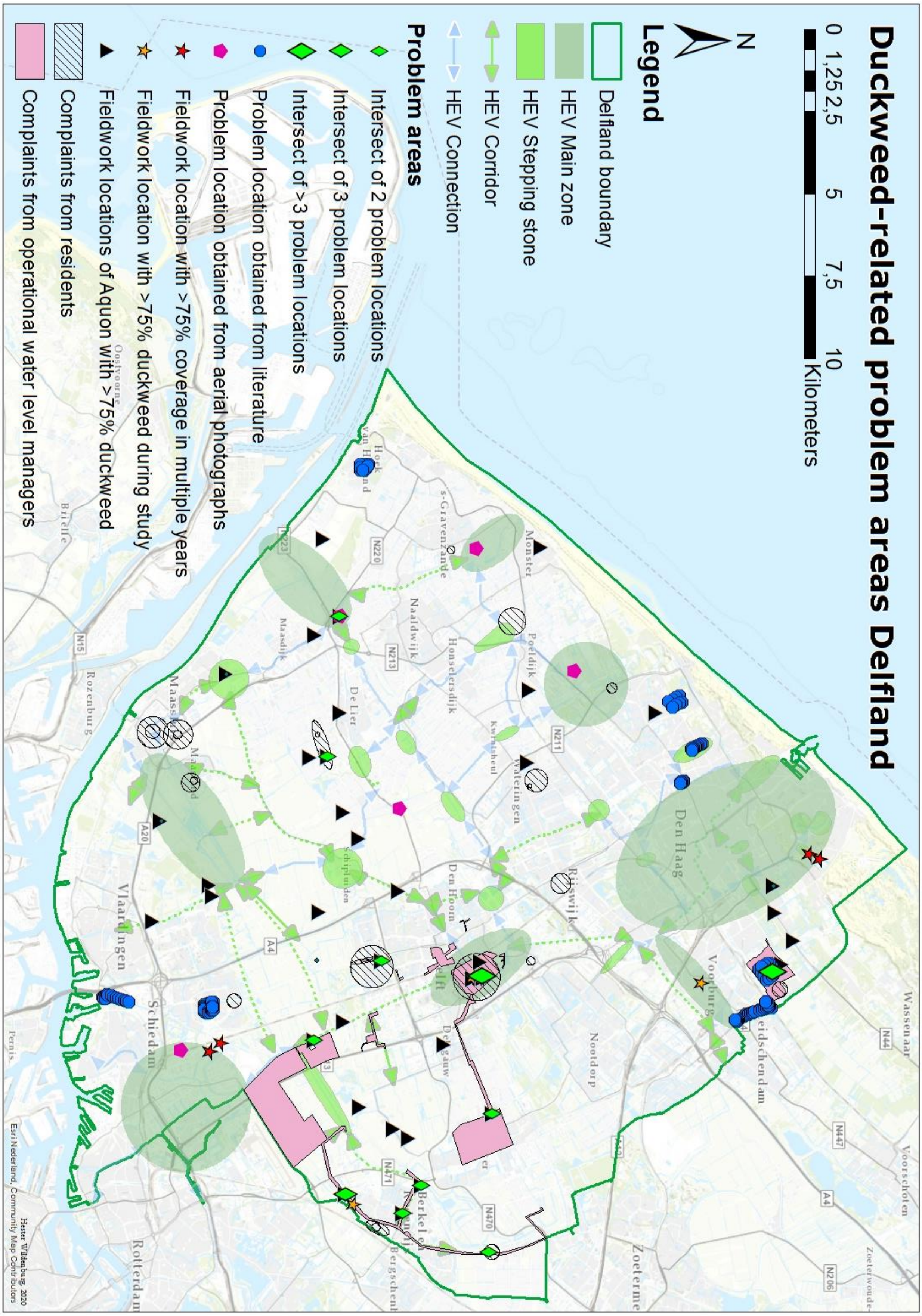
Polderweg, Schiedam



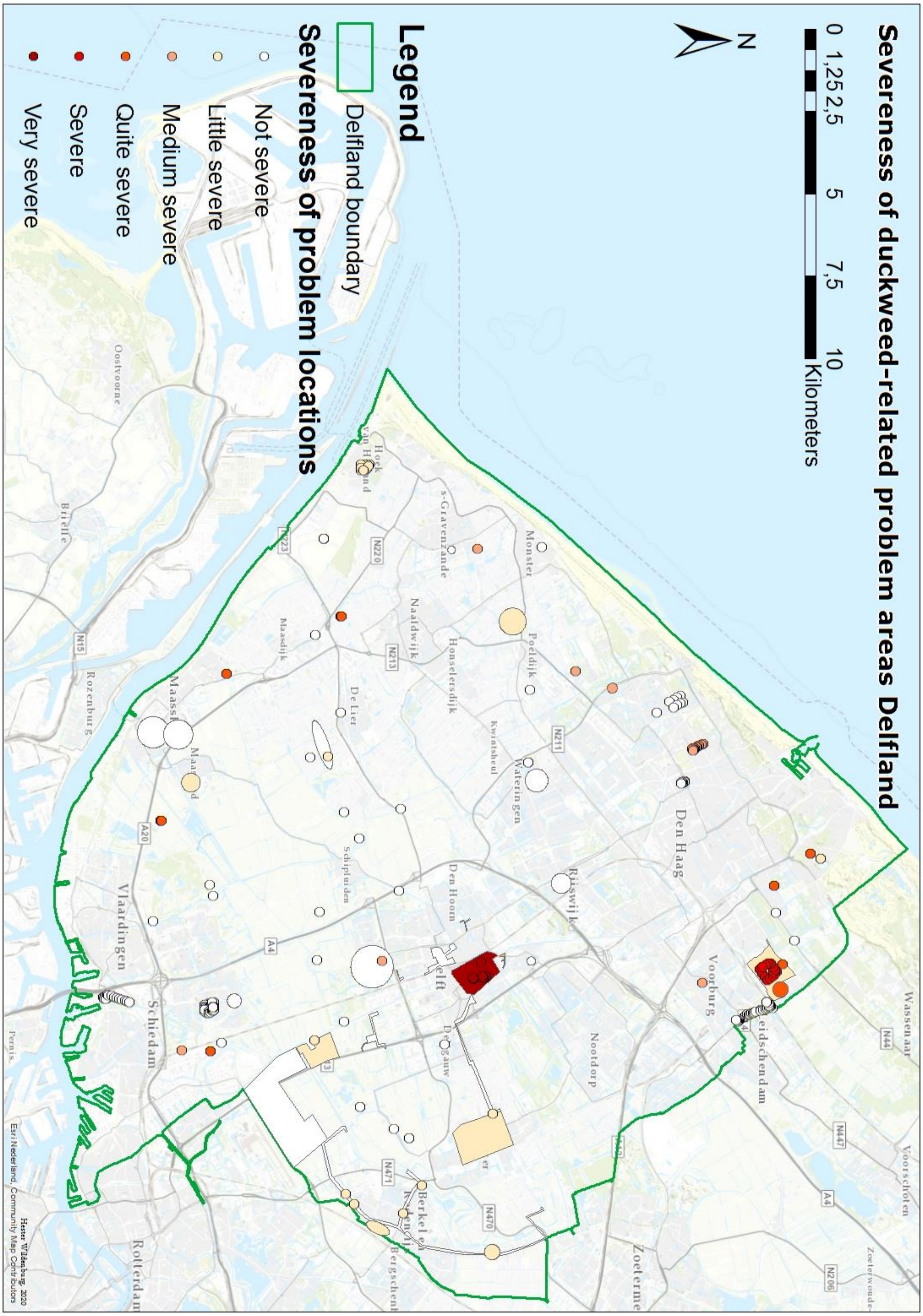
Appendix III: Duckweed-related problem areas Delfland, source map (Bezemer, 2019)



Appendix IV: Duckweed-related problem areas Delfland, detailed



Appendix V: Severeness of duckweed-related problem areas Delfland, detailed



Appendix VI: Duckweed-related problem areas based on the combined dataset