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NATURAL CONSTRUCTED WETLANDS BETWEEN WELL-TREATED WASTE WATER AND USABLE SURFACE WATER

WATERHARMONICAS IN THE NETHERLANDS (1996-2012)

RAPPORT

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08

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WASTE WATER AND USABLE SURFACE WATER

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Dit rapport is een bewerkte uitgave van Stowa-2012-12:
Waterharmonica's in Nederland; 1996-2011: van effluent tot bruikbaar oppervlaktewater

This report is a translation of the Stowa report nr. 2013-07 'Waterharmonicas in the Netherlands 1996-2012; natural constructed wetlands between well-treated waste water and usable surface water'.

Deze uitgave is ondersteund door het Waterschap Regge en Dinkel, Almelo.

DE STOWA IN BRIEF

The Foundation for Applied Water Research (in short, STOWA) is a research platform for Dutch water controllers. STOWA participants are all ground and surface water managers in rural and urban areas, managers of domestic wastewater treatment installations and dam inspectors.

The water controllers avail themselves of STOWA's facilities for the realisation of all kinds of applied technological, scientific, administrative legal and social scientific research activities that may be of communal importance. Research programmes are developed based on requirement reports generated by the institute's participants. Research suggestions proposed by third parties such as knowledge institutes and consultants, are more than welcome. After having received such suggestions STOWA then consults its participants in order to verify the need for such proposed research.

STOWA does not conduct any research itself, instead it commissions specialised bodies to do the required research. All the studies are supervised by supervisory boards composed of staff from the various participating organisations and, where necessary, experts are brought in.

The money required for research, development, information and other services is raised by the various participating parties. At the moment, this amounts to an annual budget of some 6,5 million euro.

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WATERHARMONICA

INHOUD

1

INTRODUCTION

Natural purification systems have already been used for years in The Netherlands to improve the quality of waste water before discharge or reuse. The first basic ideas design for the 'Waterharmonica' as the link between the Water Chain and the Water System were rewarded by the Foundation for Applied Water Research (STOWA) on its 25th anniversary in 1996. Since then, Waterharmonicas have been constructed in various places in The Netherlands, firstly on a small scale but now also on a large scale. Extensive research has been carried out into the working and effectiveness of these systems during over 15 years and they are still being studied. Moreover, the Waterharmonica became rooted in Dutch water policy (Uijterlinde, 2012). The picture with regard to the applications of, and research into, Waterharmonicas is summarised and discussed in the following chapters:

Ch. 2. The effluent from a STP is not a usable water
Ch. 3. The Waterharmonica, from STOWA prize to application
Ch. 4. Studies carried out in the last 15 years
Ch. 5. Waterharmonicas in The Netherlands and elsewhere
Ch. 6. How does the effluent change?
Ch. 7. What does a Waterharmonica yield apart from nature, recreation and water buffering?
Ch. 8. What does a Waterharmonica cost?
Ch. 9. Management and maintenance
Ch. 10. Design guidelines
Ch. 11. Significance of the Waterharmonica

'No fishing'

'This is treated sewage'

2

THE EFFLUENT FROM A STP IS NOT A USABLE SURFACE WATER

In The Netherlands, ground and surface water are used to make drinking and process water. After use in the Water Chain, this water is ultimately labelled as ‘waste’ and can then either be discharged or reused. However, prior to discharge or reuse, various substances present in the water must be removed. In The Netherlands, industrial discharges and discharges from treatment plants have been regulated by the Pollution of Surface Waters Act (Wvo = Wet Verontreiniging Oppervlaktewateren) since the 1970s. This act became recently incorporated with seven other water laws in the Waterwet), which went into force on 22 December 2009. This act covers most water quality issues in The Netherlands. However in underlying order in council (AMvB), ministerial regulations, by-laws and plans and, therefore, also the Decree (Surface Water Pollution Act) on Domestic Wastewater Discharges (Lozingenbesluit Wvo huishoudelijk afvalwater), hereinafter referred to as the Decree on Domestic Wastewater Discharges, include standards for discharges, agricultural use, the receiving surface water, groundwater and the reuse of waste water as process water.

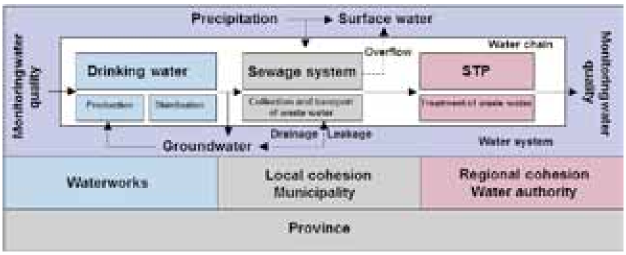
The quality of the surface water in The Netherlands, as well as in the surrounding countries, has improved greatly as a result of the aforementioned legislation and regulations. When checked against the objectives laid down in the European Water Framework Directive (WFD) the quality of the surface water of most water bodies seems to be in a reasonable state as regards the physical chemistry. This is, however, not the case by a long way when it comes to its ecology. In the language of the WFD,'it does not yet have Good Ecological Potential/ Good Ecological Status, that is, yellow, orange or red'. Each Water System is examined to see whether further reduction of substances is necessary prior to discharge into this system or whether measures carried within the Water System would be more efficient. Substantial benefits can be achieved in the discharge of treated waste water. In most sewage treatment plants (STPs) the waste water and rainwater are treated mechanically and biologically. The water leaving the STP largely meets the discharge standards for suspended solids (mainly activated sludge particles) and nutrients (phosphorus and nitrogen). The treated waste water is, however, not really natural: the oxygen concentration is low, the suspended solids contain a lot of 'loose' bacteria, comparatively speaking, the biodiversity is low and the nutrient levels are relatively high. It is, thus, reasonably clean but it is not ecologically healthy water (Schreijer, Kampf et al, 2000).

3

THE WATERHARMONICA, FROM STOWA PRIZE TO APPLICATION

The Water Chain has always had a central place in the policy plans of most water managers, and it still does. Figure 1 is derived from the 'Achtergronddocument: Beschrijving watersysteem en wettelijk kader {Background document: Description of the Water System and the legal framework}' in Friesland (Fryslân leeft met water, 2009). The flow chart was based on the Water Chain; the Water System is both the source of the water and the receiver.

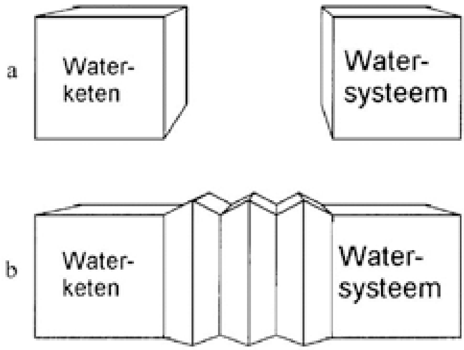
FIGURE 1 **THE CLASSICAL WATER CHAIN APPROACH, DERIVED FROM FRIESLAND LIVES WITH WATER, 2009. (FRYSLÂN LEEFT MET WATER, 2009)**



This is logical from the point of view of tackling the problem because it is also the most expensive part of the water cycle, costing approximately 3 billion annually for the whole country. These costs are distributed almost equally over the three components of the Water Chain: drinking water, sewage system and treatment of waste water.

The background document describes a close connection between the Water System and the Water Chain, such as the extraction of groundwater for drinking water supplies, the discharge of environmentally dangerous substances into the sewers, discharges from sewer overflows and STPs into the surface water, removal of groundwater by draining sewers, and discharges from leaking sewers.

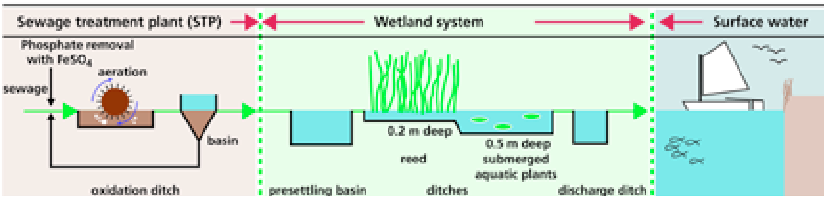
FIGURE 2 A HARMONICA FORMS A CONNECTION BETWEEN THE WATER CHAIN AND THE WATER SYSTEM: THE WATERHARMONICA (CLAASSEN, 1996)



Theo Claassen acknowledged the gap (figure 2a) between the Water Chain and the Water System a long time ago. He won the second prize at STOWA's 25 years anniversary symposium in 1996 with the submission of the concept of 'the 3D linking system: with the aid of technology and ecology, residual discharges are reduced or eliminated in physical transition zones between the Water Chain and the Water System, the linking system as a harmonica model. If the STP or the surface water cannot handle the task of polishing (post-treating) the waste water, make a surface water body between the point of discharge of the effluent of the STP and the other surface water. A surface water body of this kind can then be organised such that it can carry out its task as well as possible. The system set-up can be managed efficiently by process optimisation: 'managed nature' (Klapwijk, 1996). By deploying a natural system, the sharp, abrupt transitions between emissions and the receiving aquatic ecosystem can be softened. Figure 2b shows a diagram of this transition between the Water Chain and Water System.

This theoretical model has been further elaborated from the practical point of view, by Ruud Kampf and Theo Claassen, in the Waterharmonica: the natural link between the Water Chain and the Water System (figure 3). Purification marshes are a workable solution for changing the quality of the effluent from STPs to 'usable surface water'. Natural swamps are shallow, watery areas with a high productivity, large biodiversity and a great buffering and purifying capacity.

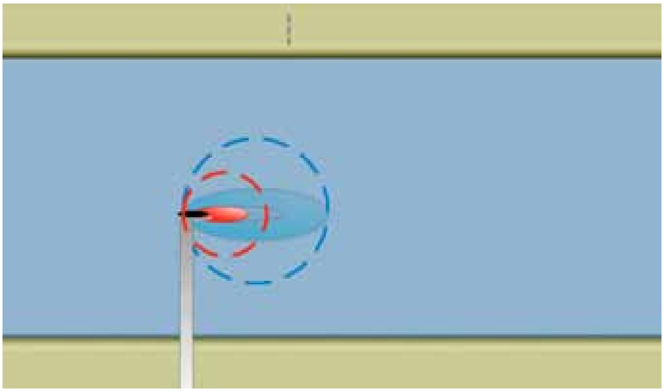
FIGURE 3 **THE WATERHARMONICA AS LINK BETWEEN THE WATER CHAIN AND THE WATER SYSTEM AT EVERSTEKOOG**



Man-made, artificial or constructed wetlands can, however, be designed and equipped to optimise this purifying and self-cleaning function.

The position of a Waterharmonica between the Water Chain and Water System is logical from the point of view of the European legislation, too. After all, it is extremely expensive and not feasible for industry and STPs to meet the strict environmental quality requirements for surface water directly at the end of the discharge pipe (Waterforum, 2008). The WFD therefore provides scope for what is known as 'mixing zones' (Baptist and Uijttewaal, 2005, Bleninger and Jirka, 2009, Bleninger and Jirka, 2010), see figure 4. These mixing zones are described as that part of a Water System which takes up a discharge in a water body before the discharge is mixed and where the concentration of a substance may be higher than the applicable standard in that directive.

FIGURE 4 **WATERHARMONICA SYSTEMS IN THE NETHERLANDS (MAP FROM GOOGLE EARTH)**



The red dashed circle indicates the ZID (Zone of Initial Dilution). Within this circle the concentration of the discharged substances may be much higher than in the water body and acute and chronic toxic effects are permissible. In the blue dashed circle outside it, the AIZ (Allocated Impact Zone) dilution must ensure that acute effects are avoided although chronic effects are permissible. Outside the blue circle, however, the applicable quality requirements for the water body must be met. Photo 1 shows this mixing with the aid of a dye.

PHOTO 1 **EFFLUENT PLUME FROM THE KATWOUDE STP, 10 MINUTES AFTER THE COMMENCEMENT OF THE DOSING OF A DYE (GHAUHARALI AND BOS, 2007)**

The above leads to the following conclusions:

- The effluent from the STP does not have to meet the requirements laid down for water bodies pursuant to the WFD;
- The discharge plume is seen as the mixing zone;
- The Waterharmonica can take over the function of the mixing zone. The quality of the water at the end of a Waterharmonica (with a low burden) comes close to meeting the applicable quality requirements for the receiving water body.

In most Waterharmonicas in The Netherlands, for the purposes of the Decree on Domestic Wastewater Discharges (Lozingenbesluit Wvo huishoudelijk afvalwater), the point of discharge is located directly after the post-settling tank of the STP. In some Waterharmonicas, a second transfer site is also designated. For example, at Land van Cuijk, there is a second discharge site after the reed ditches at which (in accordance with the Decree on Domestic Wastewater Discharges) the same requirements apply as for the outlet of the post-settling tank. At the Kaatsheuvel STP, in addition to the measuring point at the outlet of the sand filter, there is a second site after the vertical Klaterwater reed filter. ‘Standards for use’ have been formulated for the use of water from this second site in the golf and amusement park.

Apart from suspended solids during rainwater discharge, modern STPs, and particularly those with very low loads, can easily meet the discharge requirements of the Decree on Domestic Wastewater Discharges. And even more at a sludge load of 0.05 kg BOD/kg d.s. per day, or lower (Bentem, Buunen et al, 2007). Even at small STPs it is simple to achieve far-reaching nitrogen removal. Twenty years ago, the five oxidation ditches on Texel already achieved average levels of 0.6 to 1.8 mg/l of NH_4 and 4 to 8 mg/l of total N. From the practical point of view, we can conclude that, in the case of a well-designed STP (oxidation ditches) with a very low load, the NH_4 level is lower than 1 mg/l, and that ‘the rest is ok, too’ (Kampf, 2008a).

It seems advisable to enforce the ‘discharge requirements’ from the Decree on Domestic Wastewater Discharges at the outlet of the post-settling tank (or if necessary, after a subsequent system such as a sand filter). These days, however, the conversion of waste water into water

which is suitable for all sorts of purposes is becoming increasingly important. This development appears to be moving in two directions. The main direction is the direct reuse of the (treated) effluent in industry, for washing water and spraying water in towns and on golf courses, for irrigation or even directly for drinking water. The second direction is 'to give water back to nature', also applicable in urban areas. In essence, this concept is that of the Waterharmonica. Depending on the use for which the water from the Waterharmonica in question is intended, specific requirements can be laid down on its design, management and maintenance.
This can be realised by, for example, using parameters important for nature such as ammonium, nitrite, nitrate and free ammonia from the standpoint of fish toxicity, oxygen demand and uptake by algae and (aquatic) plants. Site-specific 'requirements for use' can thus be drawn up for the water leaving the Waterharmonica.

The Waterharmonica has earned itself a place in The Netherlands and abroad, and it is being applied more and more in practice, as described in the following sections. The concept has been incorporated in the policy plans of, for instance, Schieland and Krimpenerwaard (HHSK, 2012), Regge en Dinkel (Regge en Dinkel, 2005), Rijn and IJssel (Rijn en IJssel, 2009) and De Dommel (De Dommel, 2010a). But the Waterharmonica is also being applied by water managers, although it is not described in so many words in their policy documents. See Slootjes (2004), for example, for the possible application of Waterharmonicas in combating desiccation and the STOWA study into the STP 2030 (NEWater), which incorporates the Waterharmonica as an element of the water factory for supply to 'nature' (Roeleveld, Roorda et al, 2010).

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STUDIES CARRIED OUT IN THE LAST 15 YEARS

In recent years, STOWA has supported the development of the Waterharmonica in various ways, including by means of the following related studies:

- *Support of the study Uitwaterende Sluizen in Hollands Noorderkwartier'* on post-treatment of STP effluent into usable surface water in a wetland system, monitoring the Waterharmonica at Everstekoog 1995-1999 (Schreijer and Kampf, 1995, Kampf, Schreijer et al, 1996, Schreijer, Kampf et al, 2000, and Toet, 2003);
- *Handboek zuiveringsmoerassen voor licht verontreinigd water* {Manual for purifying wetlands for slightly polluted water} (Sloot, Lorenz et al, 2001);
- *Ecotoxicologische aspecten bij de nabehandeling van RWZI-effluent met behulp van biomassa kweek* {Ecotoxicological aspects of the post-treatment of STP effluent using biomass cultivation} (Blankendaal, Foekema et al, 2003);
- *Praktijkonderzoek moerassystem RWZI Land van Cuijk* {Practical research into a wetland system STP at Land van Cuijk} (Boomen, 2004);
- *Waterharmonica, de natuurlijke schakel tussen Waterketen en Watersysteem* {The Waterharmonica, the natural link between the Water Chain and the Water System} (Schomaker, Otte et al, 2005);
- *Waterharmonica in the developing world* (Mels, Martijn et al, 2005);
- STOWA Waterharmonica Workshops in Hapert and Almelo (Jacobi, 2004, see photo 2);
- *Vergaande verwijdering van fosfaat met helofytenfilters* {Extensive removal of phosphate using helophyte filters} (Blom and Maat, 2005);

PHOTO 2 **'WATERHARMONICA PROOF' STAMP IS HANDED OUT BY STOWA DURING THE WORKSHOPS AT HAPERT AND ALMELO IN 2004**

Besides the above mentioned a loose alliance was also set up between the regional water board Hoogheemraadschap Hollands Noorderkwartier, the Friesland Water Authority, Waternet, Consorci de la Costa Brava in Girona, VU University Amsterdam, University of Amsterdam (UvA) and University of Girona, with a large contribution from Netherlands Organisation for Applied Scientific Research (TNO) in Den Helder and the Royal Netherlands Institute for Sea Research (NIOZ). This study looked at the processes in effluent-fed ponds in Waterharmonicas. The study began at Everstekoog, Texel, continuing later in Horstermeer, Grou, Girona and also Garmerwolde (Kampf, Jak et al, 1999, Kampf, 2009, Kampf, Geest et al, 2007, Kampf, 2001, Foekema and Kampf, 2005, Kampf and Claassen , 2004, Kampf and Sala, 2009, Bales, 2008, Vidal, 2008, Colon, Sala et al, 2008, Pallarès, 2009, Boomen, Kampf et al, 2012a, Hoorn and Elst, 2011 and Hoorn, Elst et al, 2012). These studies led to doctoral research at VU University Amsterdam and Delft University of Technology.

In 2007, on the instructions of STOWA, a vision document was drawn up of the existing knowledge on Waterharmonica systems and listing the knowledge still required. The missing information was expressed in the form of research questions and these were prioritised as to those which needed answering in the short term and those which could wait for the longer term. This resulted in a selection of research questions. These questions were investigated in the period 2008-2011 and the results set out in the STOWA reports 2012-10 and 2012-11:

Research into suspended solids and pathogens, the main report and sub-study reports (Boomen, Kampf et al, 2012c and Boomen, Kampf et al, 2012b).

A doctoral research project of the UvA, Waternet and STOWA into 'Suspended particle dynamics in wetland systems: driving factors on concentration and composition' was also supported in this period. The WFD Innovation project 'WIPE' (Waterharmonica, Improving Purification Effectiveness) was also completed (Foekema, Oost et al, 2011 and Foekema, Roex et al, 2012). This latter project examined the risks and effects of xenobiotic substances in Waterharmonicas.

The following is based on the aforementioned studies, with additional information made available by the Dutch water authorities with one or more Waterharmonicas.

5

WATERHARMONICAS IN THE NETHERLANDS AND ELSEWHERE

The first Waterharmonica, with a surface area of 15 ha and planted up with reeds, was located near Elburg. It functioned since 1985 for years but the nutrient removal efficiency was disappointing because of the high ammonia concentrations in the effluent of the STP in those years and hydraulic short-cuts in the wetland. It has now been landscaped as a nature conservation area. In 1994, the first wetland system was laid out in accordance with the Waterharmonica concept at the Everstekoog STP on Texel. It comprised a large buffer pond after which the water flow was divided among nine parallel ditches. These ditches are shallow at the beginning and planted up with helophytes; they become deeper further up where they are full of aquatic plants. The clean water which is collected in the end ditch subsequently flows into the polder.

After Everstekoog, Waterharmonicas followed at various places in The Netherlands, including Tilburg-Noord and Klaterwater in Kaatsheuvel in 1997, Land van Cuijk in Haps in 1999, Sint-Maartensdijk in 2000, the Waterpark Groote Beerze in Hapert in 2001, Aqualân at the Grou STP in 2006, Ootmarsum in 2010 and Sint-Oedenrode in 2011. The Waterharmonicas Soerendonk and Kristalbad (between Hengelo and Enschede) went into operation in the course of 2012, as well as the extension of Everstekoog (see also www.waterharmonica.nl). Photo 3 gives an impression of the systems realised or currently being realised. Elburg was, it is true, taken out of operation in 1994, but given the extensive reports on it and the reasons for taking it out of operation at the time, it is certainly worth taking into consideration

(Butijn, 1990, Butijn, 1994 and Hut and Veen, 2004). Tilburg-Noord is 19 ha in size (gross more than 20 ha) and went into operation in 1997. Despite its size, it has always been a rather anonymous, inconspicuous Waterharmonica (Jouwersma, 1994). Because of the large amount of information available on Empuriabrava (Costa Brava, Northeast Spain), this Waterharmonica is included as a reference system in this report (Sala, Serra et al, 2004, Pallarès, 2009 and Sala and Kampf, 2011).

PHOTO 3 **IMPRESSION OF WATERHARMONICAS**

Photo 4 shows the sites of Waterharmonicas in The Netherlands. More photos of the Waterharmonicas can be found on http://www.flickr.com/photos/waterharmonica/

PHOTO 4 **SHOWS THE SITES OF WATERHARMONICAS IN THE NETHERLANDS. MORE PHOTOS OF THE WATERHARMONICAS CAN BE FOUND ON HTTP://WWW.FLICKR.COM/PHOTOS/WATERHARMONICA/)**

Various plans are being developed for other Waterharmonicas. The plans for Biest-Houtakker, for example, are very concrete (De Dommel, 2010a and De Dommel, 2011b). Plans are, furthermore, being developed for various sites, including Amstelveen, Garmerwolde, Marum, Haarlo and Dinxperlo, Ameland, Wetterlânnen, Bergumermeer, Berkenwoude, Kerkwerve and the nature reserve, the Diezemonding. The status of the various plans for Waterharmonicas varies from ‘daydreams’ to ‘very advanced’. There are also plans which, for various reasons, have not yet been implemented. These include plans elaborated for a Waterharmonica in a ‘blue-green’ wedge for the Apeldoorn STP (NN, 2004 and Veluwe, 2005) and those for a Waterharmonica for Wervershoof, which did not continue, in spite of the fact that the board of the water authority Hollands Noorderkwartier had reserved the requisite funds for it (Graansma and Schobben, 2002 and Durand-Huiting, 2005). A potential Waterharmonica in Raalte (Otte, Blom et al, 2009) has not (yet) been implemented because of the current financial situation. In 2004, Haijkens presented an inventory of STPs in the Northern Netherlands and where Waterharmonicas could be applied (Haijkens, 2004), see also (Wijngaard, 2003). See in this context also the quick scan on possible Waterharmonicas in Friesland (Kampf and Boomen, 2013).

Waterharmonicas are each constructed or designed for a specific objective. Table 1 gives the most important objectives or reasons for constructing them. This table includes not only the Waterharmonicas realised, but also those which were or are planned, with the key references to literature sources. See www.waterharmonica.nl for more detailed information; www.helpdeskwater.nl was consulted for the water managers' policy plans.

TABLE 1 LIST OF WATERHARMONICAS

NO. 0 HAS BEEN TAKEN OUT OF OPERATION; BECAUSE OF HIGH NATURAL VALUES IT HAS NOT BEEN PUT BACK INTO OPERATION

NOS. 1 TO 14 HAVE BEEN REALISED (IN THE ORDER IN WHICH THEY WENT INTO OPERATION), A TO R VARIOUS STAGES OF THE PLANNING PROCESS (ALPHABETICAL ORDER)

No.	Name	Primary reason/reasons for construction
0	Elburg	1978: to lower the nutrient level in STP effluent, taken out of operation (Butijn, 1990 and Butijn, 1994). Has not been put back into operation because of the 'high natural values' (Hut and Veen, 2004)
1	Everstekoog, Texel	1994: as a source of fresh water for agriculture on the island (Kleiman, 2006, disinfection because it crosses a residential area (Kampf, Schreijer et al, 1996). Has been expanded and renovated in 2012 – 2013 (VBK-groep, 2011 and NN, 2012a)
2	Empuriabrava, Spain	1995: to supply water for a nature reserve/to create local natural value (Sala and Romero de Tejada, 2007)
3	Klaterwater in Kaatsheuvel	1997: to produce water with a low level of nutrients and pathogens for the Efteling (Wel, 2005, Schomaker, 2010 and Schomaker, 2011)
4	Tilburg-Noord	1997: to buffer effluent during rainwater discharge so as not to exceed the maximum permissible effluent rate because of the limited capacity of the stream de Zandleij, ecologisation at basic discharge (Jouwersma, 1994)
5	Land van Cuijk	1999: to supply water to agriculture/nature and to reduce discharge to national waters (Eijer-de Jong, Willers et al, 2002 and Boomen, 2004)

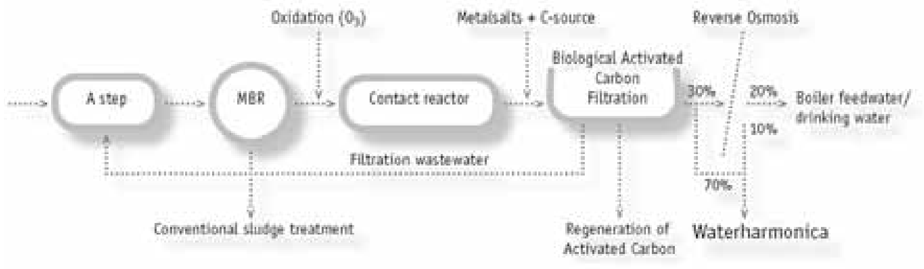
No.	Name	Primary reason/reasons for construction
6	Sint Maartensdijk	2000: to reduce nutrients and obtain insight in the functioning of the helophyte filter, recreation (Ton, 2000)
7	Waterpark Groote Beerze te Hapert	2001: river restoration Groote Beerze, to promote wet habitats (Buskens, Luning et al, 1998, Haan and Horst, 2001)
8	Aqualân Grou	2006: to develop nature and a spawning pond, demonstration project (Claassen, Gerbens et al, 2006, Boomen, Kampf et al, 2012a and Claassen and Koopmans, 2012) and Urban Water Cycle Project (NN, 2009c and Provinsje Fryslân, 2007)
9	Ootmarsum	2010: 'ecologisation' of the effluent for discharge into a small stream (Vente and Swart, 2008) and Urban Water Cycle Project (NN, 2009c and NN, 2009b)
10	Sint-Oedenrode	2011: ecological corridor, 'natural water', incorporated in a trail, bird sanctuary with watchtower (Smits, 2011 and Smits, Scheepens et al, 2011)
11	Kristalbad (Enschede/ Hengelo)	2012: regional buffering water, recreational green buffer zone, ecologisation, improvement of water quality (Regge en Dinkel, 2011b and Regge en Dinkel, 2011a) and Dutch WFD subsidy (Agentschap NL, 2011, NN, 2009a)
12	Soerendonk	2012: water buffer, recreation, to develop natural habitats, spawning pond/fish migration (De Dommel, 2010b, Jannsen, Zandt et al, 2010, De Dommel, 2012c, and Zanten, 2012) and Dutch WFD subsidy (Agentschap NL, 2011, NN, 2009a)
13	Tilburg Moerenburg	2011-2012: to buffer 'influent', improving natural values, recreation, to prevent overflow (Boomen, 2007 and De Dommel, 2012a) www. moerenburg.nl
14	Vollenhove	2012 'purifying riverbank' (Blom and Sollie, 2009)
a	Ameland	to supplement groundwater in desiccated dunes, to create a current to attract migratory fish (attraction current), conservation, in preparation ((Kroes, 1997, Min, 2002 and Lange and Veenstra, 2007)
b	Amstelveen	to supply water to the urban area, in preparation (AGV, 2011, Leloup, Voort et al, 2012)
c	Apeldoorn	feasibility study, cost and benefit analysis, 'Blue-green wedge', planning and elaboration, not implemented (NN, 2004, Prakken, 2003 and Veluwe, 2005)
d	Arnhem	for use as urban water, not yet realised (Arcadis, 2004)
e	Bergumermeer-Wetterlânnen	natural water, water buffer, Dutch WFD subsidy (Projectgroep Wetterlânnen, 2011a and Projectgroep Wetterlânnen, 2011b) and Dutch WFD subsidy (Agentschap NL, 2011, NN, 2009a)
f	Berkenwoude	to remove nutrients, to make 'living' water, buffering, in preparation (HHSK, 2011 and HHSK, 2012)

No.	Name	Primary reason/reasons for construction
g	Biest-Houtakker	to make 'natural and living' water, to remove suspended solids during rainwater discharge (bypass sand filter), landscaping, under design (De Dommel, 2011b)
h	De Cocksdorp	'Stickleback system' – administrative approval, not implemented (Kampf, 2002, Blankendaal, Foekema et al, 2003, Foekema and Kampf, 2002 and Jak, Foekema et al, 2000)
i	Dinxperlo	water garden and green zone (Waterforum, 2012 and Oosterhuis and Schyns, 2013)
j	Dreumel	to supply water to a future nature reserve Over de Maas (Marsman, 2006)
k	Garmerwolde	to reduce suspended solid discharge, preparatory study (Hoorn, Elst et al, 2011 and Hoorn, Elst et al, 2012)
l	Geldermalsen	water storage, fish stock and migration, recreation, procedure was temporarily stopped after the draft design (Marsman, 2009 and Graaf and et al, 2010)
m	Gieten	natural water, nutrient removal (Haijkens, 2004)
n	Kerkwerve	'Perpetual Motion', draft design (Hoekstra, 2011)
o	Marum	to supply water to the nature reserve, in preparation (Haijkens, 2004 and, Oranjewoud, 2010)
p	Raalte	feasibility study, cost and benefit analysis, natural water, postponed (Otte, Blom et al, 2009)
q	Vlieland	to reuse STP effluent for drinking water supplies, nature, groundwater, negative advice but is being reconsidered (personal communication Theo Claassen and IWACO, 1993 and Vlaski, Hoeijmakers et al, 2006)
r	Wervershoof	ponds for disinfection, administrative approval, not implemented (Graansma and Schobben, 2002 and Durand-Huiting, 2005)

The functional objectives of a Waterharmonica are, therefore, often different and the design customised. During the design, various components can be opted for and the actual dimensions and load determine how the system works. The existing systems do not all receive the entire output from the STP (see table 2). Those at Aqualân Grou and Land van Cuijk, for example, receive approx. 25 % of the output of the STP. In both cases, this choice was based on the fact that more room was simply not available. In Land van Cuijk, there was enough to supply the stream, the Laarakkerse Waterleiding, with water. In 1997, Tilburg-Noord was realised, as water storage, on the site of the former sewage farms because the discharge capacity of the stream, the Zandleij, is not adequate to drain the entire effluent during wet weather.

From the reuse standpoint, the Waterharmonica can be viewed as a consumer of water from the water factory. By way of illustration, a sample configuration from the second NEWater workshop held on 14 October 2009 (Roeleveld, Roorda et al, 2010) is shown in figure 5.

FIGURE 5 **SAMPLE CONFIGURATION OF THE WATER FACTORY, DRAWN UP DURING A NEWATER WORKSHOP (ROELEVELD, ROORDA ET AL, 2010)**



Waterharmonica systems are, therefore, laid out in different ways. Land van Cuijk (Eijer-de Jong, Willers et al, 2002) and Grou (Claassen, Gerbens et al, 2006) are based on Everstekoog. Soerendonk is, in turn, derived from Grou (Sluis, Westerink et al, 2009). As shown in figure 3 and photo 3 these Waterharmonicas all consist of a settling pond/ Daphnia pond, followed by reed ditches and then a deeper part with aquatic plants:

- a settling pond to catch the sludge which overflows from the STP during rainwater discharge and can be drained to enable the easy removal of this sludge, if necessary. The pond can also serve to distribute the water between the various ditches. The wind must be taken into account here as it can cause uneven distribution and churns up the sludge. At Everstekoog, large numbers of Daphnia (up to approx. 300/l) have been counted. These high densities subsist because of a lack of predators in the pre-settling basin (Schreijer, Kampf et al, 2000). At Everstekoog, the level of algae, expressed in chlorophyll a, was low due to predation by the Daphnia (< 8 μg/l). These observations were the reason for the commencement of the study into the role of Daphnia in the biological filtration of suspended solids, including pathogens and algae (Kampf, Jak et al, 1999).

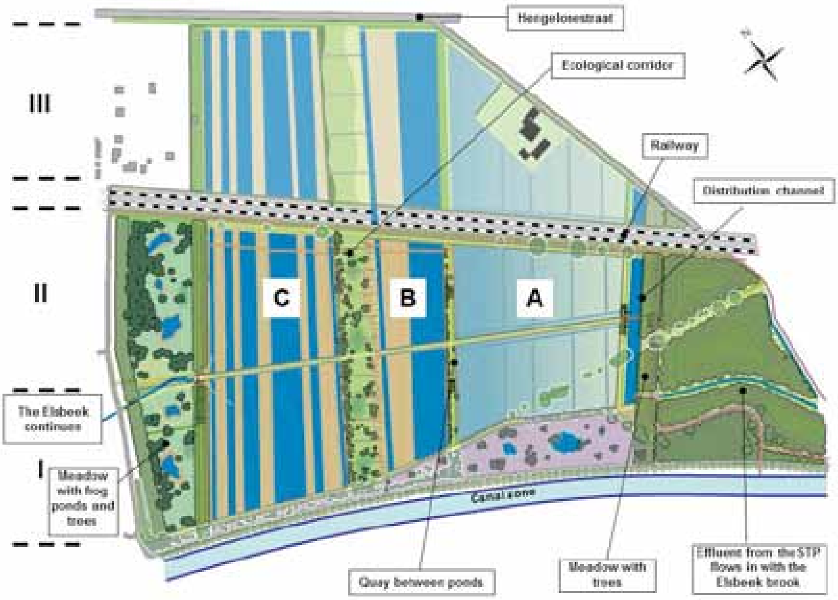
- shallow ditches with aquatic plants. Research has shown that reed is preferable to reed mace because of the significantly larger surface area it provides for biofilm formation (Schreijer, Kampf et al, 2000);
- a system with submerged aquatic plants at the end of the Waterharmonica brings about the build-up of a more or less complete functioning aquatic ecosystem. At Grou and Soerendonk, this latter compartment is laid out as a fish spawning pond which is connected to the surface water (Claassen, Gerbens et al, 2006 and Claassen and Koopmans, 2012). The similarity of Empuriabrava in Spain has led to intensive cooperation (Sala and Kampf, 2011). Instead of constructing fish spawning ponds like those at Grou and Soerendonk, the last part has been developed as marshy pasture land which attracts a great many birds (Sala, Serra et al, 2004). The Waterpark Groote Beerze in Hapert has a comparable structure, but also has a swamp forest (Haan and Horst, 2001).

Besides the aforementioned structured Waterharmonicas, various low-budget versions have also been constructed. Ootmarsum does not have a ‘Daphnia pond’, but it does have reeds and a pond (Vente and Swart, 2008). Sint-Maartensdijk has a reed bed with a sub-surface wetland, a structure known as a ‘root filter’ (Ton, 2000). A third Waterharmonica realised in 2012 is that at Vollenhove (Blom and Sollie, 2009) . As is the case with Sint-Maartensdijk, Sint-Oedenrode and Elburg, this is a low-budget model, those involved having tried to realise it using simple means, see photo 3.

Klaterwater is different in the sense that it is fed with effluent (approx. 10 % of the output) which has already been subjected to continual sand filtration, with a fairly high Fe dosing to maximise the P removal, at the Kaatsheuvel STP. This is followed by a vertical reed filter and a system of ponds on the golf course (Smits, 2006) and in the Efteling (Schomaker, 2011). Also in Land van Cuijk and Soerendonk the effluent is subjected to sand filtration before being led to the Waterharmonica. The STP Ootmarsum is a hybrid with both an activated-sludge plant with a sand-filter and a MBR (membrane biofilm reactor).

There are also Waterharmonica systems which have been designed to buffer peaks in precipitation. The city of Tilburg has two Waterharmonicas, in which high flows during rainy periods are buffered. Initially, in 1997, a Waterharmonica was constructed behind the Tilburg-Noord STP to buffer the effluent during rainwater discharge. This was necessary because, as a result of the increase in effluent flow rates, the receiving Water System could no longer handle the discharge. Because of the abolition of the Tilburg-Oost STP and the transport of the rain and waste water to Tilburg-Noord, the load was to become even greater. In order to prevent this, the old Tilburg-Oost STP was converted into a large natural buffer for untreated waste water (Moerenburg). The joint storage capacity of Tilburg at Moerenburg and at Noord is approx. 300,000 m^3. A striking point is that, in approx.

DIAGRAM 1 **OVERVIEW OF KRISTALBAD. EXPLANATION, SEE TEXT**



half of the time, the quality of the water in the Moerenburg storm Waterharmonica becomes so good that it meets local discharge requirements. The concept of the 'storm Waterharmonica' was introduced in order to distinguish this type of Waterharmonica from the other types, and to anchor its place in the water cycle (Boomen, Kampf, 2013, in preparation).

Kristalbad was constructed recently (2012), diagram 1. This Waterharmonica can also collect peak supplies and its design is the reverse of Empuriabrava: a marshy wetland is the first step in the Waterharmonica, followed by alternating ponds and reeds, the 'bar code of the Kristalbad' (Tubantia, 2011, Regge en Dinkel, 2011b).

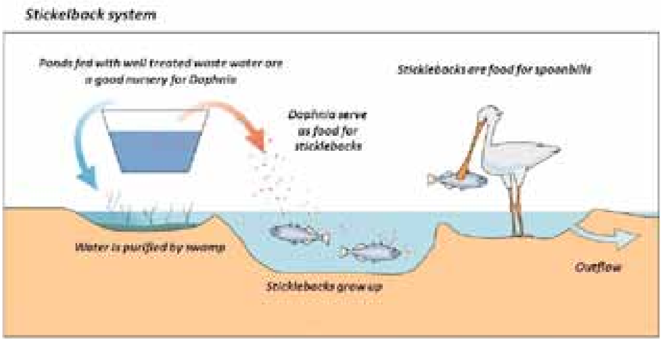
The effluent from the Enschede STP flows through the brook Elsbeek past FC Twente's soccer stadium and the ice rink to the distribution channel where it is divided into three flows. A valve has been installed in the supply channel to each flood plain (A I, A II and A III), so that the lines can be loaded alternately. The first line is filled for 4 hours. In the successive 8 hours, the flood plain in question runs empty and is dry (or swampy). During this 8-hour period, the second and third lines are filled successively. After 12 hours, the cycle is repeated. During periods of high supply rates, however, the water flows via overflow thresholds from the distribution channel to the flood plain or the Kristalbad will even fill up completely and function as a water storage basin. The water flows from the flood plain through the reed filter (B) to the wetlands (C). Ultimately the water is returned via the overflow to the brook Elsbeek. The meadow with trees is just ornamentally, for nature. Since the Kristalbad is fairly deep on average, the hydraulic retention time (4 days at the average rate of supply) is fairly long. The retention time decreases to 2.4 days in the event of rainwater discharge, but this only takes place after the entire storage capacity of more than 254,000 m^3 has been used up. If the basic supply to the Kristalbad of 40,000 m^3/day increases to the maximum supply of 140,000 m^3/day; it takes two and a half days before it is full and the total storage capacity is in use.

The best components to use and the best order in which to construct these components have not, as yet, been worked out; this area is still undergoing a learning process. A few important aspects are given below:

- It is clear that active sludge flocks are primarily removed by settling and that loose bacteria form an attractive source of food for Daphnia (and other zooplankton), thus forming the beginning of an active food chain in the Waterharmonica. These large numbers of Daphnia also ensure that there is no algae bloom and that the water stays very clear despite the high levels of nutrients (Kampf, Jak et al, 1999). Whether it is always advantageous to place a filtration step before the Waterharmonica (technical, membrane bioreactor (MBR), sand filtration) or in the Waterharmonica (natural or sand filtration with an extremely low load) is still not yet clear. The filtration step, in combination with chemicals, can lead to low phosphate levels, as is the case at Klaterwater where the water in the ponds contains less than 0.1 mg total P. At Klaterwater, the removal of pathogens that takes place in the vertical flow constructed wetland (which is located after the sand filter) is fairly low. This helophyte filter also ‘produces’ suspended solids which wash out incidentally (compare with ‘shedding’ from oxidation beds) (Boomen, Kampf et al, 2012b, sub-study 4).
- The reed ditches in most systems are line-shaped elements which are laid out parallel to one another to prevent dead zones and create plug flow. They are relatively shallow (20-50 cm deep). The width of the ditches is determined by the reach of the machines used for maintenance, mainly reed harvesting in winter.
- This was not an option for the Kristalbad because of its size. It was, therefore, made such that the whole thing can be flooded and mowed using mowing boats.

The combination of the ‘stickleback system’ and the fish pass at the pumping station for the De Cocksdorp STP was thought up in the autumn of 2000. Daphnia are cultivated in the Daphnia pond and form food for the sticklebacks brought in by means of the fish pass. The water subsequently flows through a shallower wetland system where spoonbills can enjoy the sticklebacks. The outflow is subsequently used to lure fish to the fish pass (see figure 6). Despite all the publicity it received (Texelse Courant, 2001, De Volkskrant, 2002, Noord-Hollands Dagblad, 2002, Foekema and Kampf, 2002, Kampf, Eenkhoorn et al, 2003). The time was then not yet ripe for this concept; that time may now have come, elsewhere.

FIGURE 6 **THE WATERHARMONICA AS 'FOOD CHAIN' APPROACH, FROM PARTICLES IN WASTE WATER, VIA DAPHNIA AND STICKLEBACKS TO SPOONBILLS (BASED ON THE DE VOLKSKRANT, 2002)**



The Wetterskip Fryslân still has concrete plans for Waterharmonicas on the Frisian islands, particularly on Ameland. The Frisian Wadden islands constitute one of the 'pearls' of Friesland and the aim is to realise a sustainable, closed Water Chain on each of the islands. An implementation programme is therefore being drawn up by all the parties involved (Min, 2002, Lange and Veenstra, 2007). In 2012, a feasibility study into the possibility of Waterharmonicas in the province of Friesland was carried out for Wetterskip Fryslân (Kampf and Boomen, 2013). The value, necessity and possibilities of Waterharmonicas were considered from two points of view: that of the Wetterskip's task: management of the water quality and quantity, and that of the available land, spatial planning, nature and landscape. The outcome was rather surprising; in the long term (2012-2027), it would be possible to construct a Waterharmonica after practically every STP. This would, of course, require close cooperation with neighbouring land users, residents, nature managers, municipalities and other authorities. See also chapter 10.

Table 2 shows the characteristics of Dutch Waterharmonica systems operating in 2011 (Elburg is included although it is no longer in operation) (Boomen, Kampf et al, 2012b, sub-study 4). The hydraulic load is given for the net surface areas constructed for the 'purification' processes in the Waterharmonica.

TABLE 2 **SOME CHARACTERISTICS OF DUTCH WATERHARMONICA SYSTEMS**

System	Surface area		Flow rate	Net hydraulic load	Retention time	Percentage of effluent
	(ha)	netto	(m^3/day)	(m/day)	(day)	(%)
Aqualân Grou	1.3	0.8	1,200	0.15 [a]	3.3 [a]	approx. 25 [a]
Elburg	18.9	15	10,000	0.07	15	100
Everstekoog on Texel	2.7	1.3	3,500	0.27	2 [b]	100
Klaterwater in the Kaatsheuvel [c]	See[c]	7,1	1,380	0.02	105	approx. 10 [c]
Kristalbad [d]	40	21.5	35,750	0.18 [d]	4.6	100
Land van Cuijk in Haps	7.7	3.6	8,650	0.24	4	approx. 25
Ootmarsum	4.4	2.3	3,030	0.13	3.7	100
Sint Maartensdijk	4.8	1.0	2,400	0.24	1.5	100
Sint-Oedenrode	4.7	-	16,000	-	?	
Soerendonk	6.6	2.8	5,000	0.18	4	
Tilburg-Moerenburg [e]	7.5	5	0 - 54,500	approx. 1	2	N/A
Tilburg-Noord [f]	20	19.5	41,500-275,000	0.75-1.4	2-1.2	100
Vollenhove	1.2	1.0	1,500	0.15	4.3	100
Waterpark Groote Beerze in Hapert	5.2	3.8	7,200	0.19	2.8	100

a: Aqualân: from 2012 the load has been lowered to 480 m^3/day, this leads to an hydraulic retention time of 8 day, and only 10 % of the effluent flow.

b: Everstekoog: During the study 1995-1999, retention times between 1.6 and 11 days.

c: Klaterwater: depending on the water requirement in the Efteling approx. 10 % of the effluent is treated by sand filtration with far-reaching P removal at the STP. No gross surface areas are given because Klaterwater forms part of the amusement park and golf course.

d: Kristalbad: During rain water flow buffering, the wet surface area is 28.5 ha, and 160,000 m^3 water is buffered. With rainwater discharge, it takes almost 2 days before the buffer is full. See the text for an explanation of the Kristalbad.

e: Tilburg-Moerenburg. This system is an isolated Water System which only serves as a buffer during rainwater discharge. Approx. 54,500 m^3 can be stored on a temporary basis in the buffer system.

f: Tilburg-Noord. The low flow rates and hydraulic loads stated apply during dry weather discharge and rainwater discharge respectively. In the event of rainwater discharge, the water level rises by a maximum of 1.6 to a maximum water storage of 240.000 m^3.

Waterharmonicas in The Netherlands occupy one or more hectares, Kristalbad being the largest (40 ha) because various functions were assigned to the planned water storage in the green buffer zone between Hengelo and Enschede. The depths of the various elements vary from 0.2 to 2 m. Some Waterharmonicas are fed with a proportion of the effluent of their respective STPs (Grou, Land van Cuijk and Klaterwater), but most receive the entire output (and therefore also the rainwater discharged). Tilburg-Noord and Kristalbad were specifically designed for water storage.

Most Waterharmonicas receive a water layer varying from 10 to 30 cm per day and have a retention time of two to four days. Elburg received only 0.07 m per day and, because of its relative large excessive depth, had a long retention time of 15 days. An exception is the low load at Klaterwater, to which a number of large ponds are linked. Tilburg-Noord, designed for water storage, receives the highest load. Chapter 9, Design guidelines, examines in detail the relationship between the dimensions and load with achieving the objectives.

Mesocosm research has been carried out at various Waterharmonicas to provide insight into the details. Larger decreases of P and N, for example, were achieved under these structured circumstances. These mesocosms have been located at Everstekoog, Horstermeer, Grou, Empuriabrava in Spain (Kampf, 2009) and Garmerwolde (Hoorn, Elst et al, 2011 and Hoorn, Elst et al, 2012), see photo 5.

PHOTO 5 **SET-UP OF MESOCOSMS FOR THE WATERHARMONICA STUDY, WITH PERIODS OF RESEARCH**

Everstekoog 1998-2006

Horstermeer 2006-2010

Grou 2007-2010

Empuriabrava from 2007

Garmerwolde from 2010

This report focuses on The Netherlands but various links have been established with other countries in relation to the Waterharmonica. The water authority Regge en Dinkel received support in designing Ootmarsum and the Kristalbad from Sweden (WRS Uppsala, University of Linköping) because of its experience with wetland systems which show many of the characteristics of Waterharmonicas (Andersson and

Kallner, 2002, Andersson, Ridderstolpe et al, 2010 and Flyckt, 2010). These systems are comparable in size 1.6 - 28 ha and have been in operation for some time (up to 20 years). Empuriabrava (Costa Brava, Northeast Spain) was constructed according to Waterharmonica principles and this formed the basis for long-term cooperation with Consorci de la Costa Brava, the water cycle company, and the University of Girona (Sala and Kampf, 2011). Jung-Hoon described experimental and full-scale Waterharmonicas during a recent symposium in South Korea (Jung-Hoon, 2011). In recent years, the Waterharmonica has been discussed on various EU occasions, such as the EUREAU Water reuse group. A workshop held by the EU Neptune project in Varna, Bulgaria (Kampf, 2008c), showed that the Waterharmonica in Eastern Europe can be an inexpensive alternative for improving the effluent quality of an STP which does not function optimally. Examples include Põltsamaa in Estonia (ponds of 1.2 ha in surface area and a retention time of 10 days, the primary objective being to reduce suspended solids and biological oxygen demand (BOD) in the effluent) and Yulievsky in Ukraine (inexpensive alternative to the expansion of a poorly functioning STP). For a list of lectures at international congresses and meetings, see www.waterharmonica.nl/conferences.

As a result of its simplicity, the Waterharmonica is also a very workable option for application in developing countries. It appears to be a good continuation of a simple, traditional approach to waste water treatment, the oxidation ditch (Pasveer, 1957 and Kampf, 2008b). The STOWA report on the Waterharmonica in the developing world (Mels, Martijn et al, 2005) gives a good picture of the situation. In 2005, Chanzi Hamidar gave a lecture (Chanzi, 2005a, Chanzi, 2005b) on its potential for application in Tanzania as an alternative to ecosanitation: 'if someone is rich enough to flush his/her toilet with drinking water, let him/her pay for the collection and treatment of waste water with the objective of returning the water, in a good state, to the natural environment or using it for some other good purpose'. Together with the water authority Hoogheemraadschap De Stichtse Rijnlanden and with the support of Aqua for All, the water board De Dommel has already taken over the suggestions in the STOWA report for use in Nicaragua (Aqua for All, 2009, De Dommel, 2011a).

6
HOW DOES THE EFFLUENT CHANGE?

An important objective of the Waterharmonica is to change the water in both the physical-chemical sense and the ecological sense. Various studies have been carried out in The Netherlands and abroad in recent years to determine whether and how this takes place in a Waterharmonica. These studies vary from routine monitoring to practical research, but also to doctoral research: Sylvia Toet (Utrecht University), Ruud Kampf (VU University Amsterdam/ Delft University of Technology) and Conxi Pau (University of Girona, Spain). Furthermore, monitoring programmes have been linked to the new Waterharmonicas which will yield new knowledge in the future.

Our existing knowledge with regard to Waterharmonicas is summarised below, with attention to:

- the change in suspended solids;
- functioning under peak loads;
- nutrients;
- organic substances and oxygen management;
- pathogens;
- ecotoxicology and xenobiotic substances;
- ecology

CHANGES IN SUSPENDED SOLIDS (SUSPENDED SOLIDS PARADOX)

During a meeting held in 2007, which was laid down in the Waterharmonica Vision Document (Boomen, 2008), it became apparent that suspended solids was the most pressing issue. There were three reasons for this:

1 The wider attention for the removal of suspended solids of effluent-filtration technologies at STPs: can Waterharmonica systems do this better or more cheaply or does it lead to supplementary removal?

2. What is the effect of sludge overflow from an STP under rainwater discharge conditions? Is it buffered?

3. Disinfection, and how it can be optimised.

Existing knowledge of the nature of suspended solids and the usability of the usual analysis methods (with a high detection limit) yields insufficient information to enable us to answer these questions. This led to the STOWA Waterharmonica study, research into suspended solids and pathogens (Boomen, Kampf et al, 2012c), and a fourth doctoral study: that of Bram Mulling (UvA).

The various studies have shown that the total quantity of suspended solids in a Waterharmonica usually remains the same or increases. This is the result of two processes. In the beginning, the suspended solids from the STP decrease in the Waterharmonica due to settling, consumption and decomposition. At the same time, suspended solids are formed: algae and zooplankton (Daphnia), macro-fauna, etc. The Daphnia ensure that there is no excessive algae growth.

The total quantity of suspended solids may decrease in the middle of the Waterharmonica as a result of these processes, but at the end, the quantity may increase again. This is the so-called ‘suspended solids paradox’ (Schreijer, Kampf et al, 2000, Kampf, 2009). Figure 7 illustrates this.

FIGURE 7 **SUSPENDED SOLIDS HYPOTHESIS (KAMPF, 2009)**

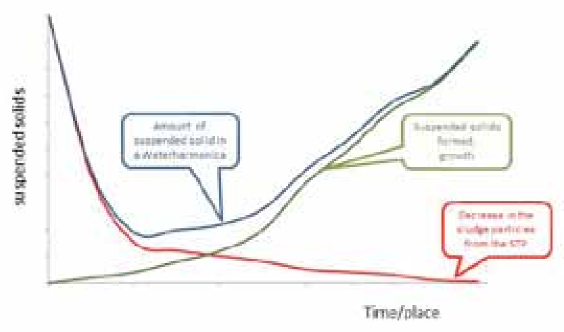
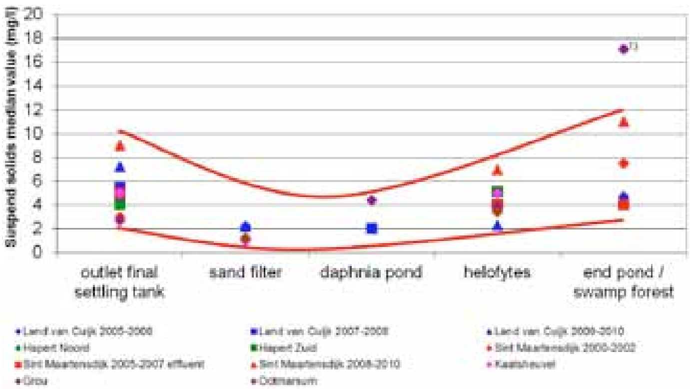


Figure 8 shows the results of measurements of suspended solids at various Waterharmonicas throughout The Netherlands in recent years (Boomen, Kampf et al, 2012c). The presence of Daphnia ponds, reed ditches or a sand filter at the beginning of the Waterharmonica lowers the median values of the suspended solids to even lower values. In the last elements of the Waterharmonicas (aquatic plant ponds, swamp forest or spawning ponds) the absolute quantity of suspended solids increases again, although the values are still low compared with these in Dutch surface waters.

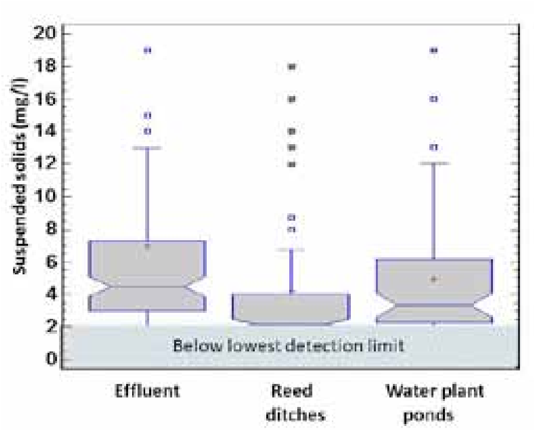
FIGURE 8 **THE SUSPENDED SOLIDS PARADOX MEASURED; MEASUREMENTS FROM 11 SYSTEMS IN THE NETHERLANDS (MEDIAN VALUES) (BOOMEN, KAMPF ET AL, 2012B, SUB-STUDY 4)**



1) = measurement from the spawning pond at Aqualân Grou. This corresponds closely to the curve for the surface water of the Kromme Grouw.

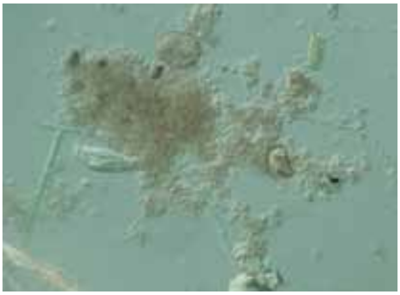
Figure 9 illustrates this in more detail on the basis of measurements of the suspended solids in the Waterharmonica at Land van Cuijk taken over the period 2005-2006 (Boomen, Kampf et al, 2012c). A clear decrease in the quantity of suspended solids can be detected from the outlet of the post-settling tank to after the helophyte filter (average value decreases from 7.0 to 4.2 mg/l). However, the level of suspended solids increases after the aquatic plant ponds (average value increases from 4.2 to 5.0 mg/l). In the Box-whisker plots illustrated, the average value is indicated by the red plus symbol, and the median by the line through the middle of the notching of the box.

FIGURE 9 **THE SUSPENDED SOLIDS PARADOX MEASURED; MEASUREMENTS FROM LAND VAN CUIJK 2005-2006 (BOOMEN, KAMPF ET AL, 2012B, SUB-STUDY 4)**

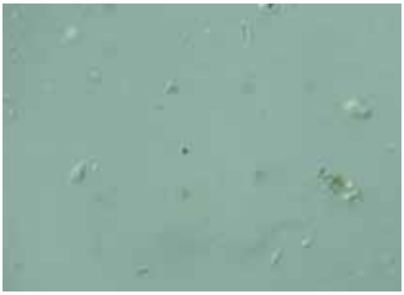


Despite the fact that the quantity of suspended solids in Waterharmonicas does not often decrease in the absolute sense, the composition changes greatly: the solids become much more ‘natural’. This is well illustrated by microscopic photos of the water with suspended solids. Photo 6 shows the change that takes place in the suspended solids originating from the post-settling tank in the Waterharmonica at the Everstekoog STP. This change in particle composition was confirmed by a study of the Grou system in 2010 (Boomen, Kampf et al, 2012a).

PHOTO 6 **THE COMPOSITION OF SUSPENDED SOLIDS CHANGES IN A WATERHARMONICA (EVERSTEKOOG, PHOTOS BY ANNIE KREIKE, WATERPROEF)**



STP EFFLUENT WITH SUSPENDED SOLIDS ORIGINATING FROM THE ACTIVE SLUDGE PROCESS

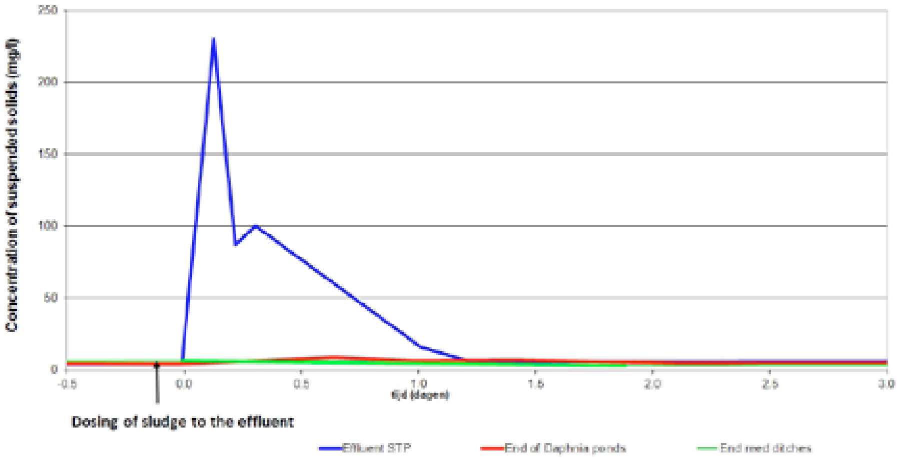


MORE NATURAL SUSPENDED SOLIDS AT THE END OF THE WATERHARMONICA

PEAK LOADS

As a result of the highly varied supply of water to a STP, the flow rate and the quality of the effluent also vary. These variations are, to a large extent, buffered in a Waterharmonica. The big advantage is that, even with a simple Waterharmonica, there is far less risk of the standards being exceeded. The STOWA study '*Waterharmonica, onderzoek naar zwevend stof en pathogenen* {Waterharmonica, investigation into suspended solids and pathogens}' (Boomen, Kampf et al, 2012b) showed that this applies to both the peak buffering of suspended solids and the buffering of nutrients and bacteria. For example, more than 90% of the suspended solids from a sludge overflow, with values greater than 200 mg/l, are buffered in the first ponds. The very high concentrations of total phosphorus and total nitrogen at the outlet of the post-settling tank during the sludge overflow had also decreased by 90% and 60-70% respectively by the end of the reed ditches. Figure 10 shows the change in concentration of suspended solids during and after a sludge overflow in the various elements at Aqualân Grou.

FIGURE 10 **CHANGE IN CONCENTRATION OF SUSPENDED SOLIDS IN THE SUCCESSIVE WATERHARMONICA COMPONENTS AT AQUALÂN GROU DURING AN ARTIFICIALLY INDUCED SLUDGE OVERFLOW (NOVEMBER/DECEMBER 2009) (BOOMEN, KAMPF ET AL, 2012B, SUB-STUDY 3)**



This decrease in suspended solids is related to settling of sludge. If the objective is to buffer a peak load, this must be taken into account when designing the Waterharmonica. That is, a pond must be located before a reed system, and it must be possible to clean the pond easily. The WIPE study showed that peaks in micro-organisms and xenobiotic substances are also levelled at the same time, without the Waterharmonica system suffering from appreciable negative (eco-toxicological) consequences (Foekema, Roex et al, 2012). This also corresponds with the observations from the STOWA study regarding biomass cultivation (Blankendaal, Foekema et al, 2003).

The extent to which the high sludge removal in a Waterharmonica can lead to savings in the dimensions of, for example, a post-settling tank, is still unclear. Savings may well be plausible because the greater part of the volume from the post-settling tank is intended for the separation of larger active sludge particles under rainwater discharge conditions. Under dry weather conditions, the small particles remain in the post-settling tank but they can wash out under rainwater discharge. If the post-settling tank is smaller, the Waterharmonica will thus have to handle larger as well as smaller particles. The measuring results show that these particles can easily be captured in a Waterharmonica (Boomen, Kampf et al, 2012b, sub-study 3). The manageability of the settling process in the post-settling tank is, however, important because the settled active sludge is needed for the treatment process.

NUTRIENTS

The nitrogen and phosphorus cycle in natural systems is rather complex. In the STP, a number of these processes are conditioned to achieve nutrient removal. A Waterharmonica is, on the other hand, more a case of ‘natural wet nature’ (or ‘wet agriculture’). It is similar to wet grassland. The optimum rate of fertiliser application for wet grassland is, for example, 400 kg N/ha/year, 60-80% of the nitrogen application being converted into plant material and the rest disappearing through denitrification and ammonia release (Hoeks and et al, 2008). There is no more than 500 to 1,200 kg N/ha in the soil itself. It is important to realise that agriculture is not possible without nitrogen application, ammonia escape and denitrification being seen as ‘loss’. In a Waterharmonica, some of the nitrogen can thus be captured in plants or can escape, but the N removal is limited. There is, therefore, no harm in looking at the fate of nutrients in Waterharmonicas from an agricultural standpoint and using agricultural knowledge of fertiliser application (see for example Hoeks and et al, 2008). Capture in plants (approx. 400 kg/ha/year) is probably responsible for only a part of the removal and, certainly in the case of shorter retention times (= higher loads), denitrification and ammonia escape play a significant role, as shown in figure 11. This figure also shows several other sources of nitrogen. The loads at Everstekoog described above are shown with red dashed lines.

FIGURE 11 **TOTAL N REMOVAL AT RETENTION TIMES OF 1.3 TO 11.3 DAYS AT EVERSTEKOOG PLOTTED WITH THE RESULTS OF WETLAND SYSTEMS (KAMPF, 2005B, AFTER TOET, 2003)**

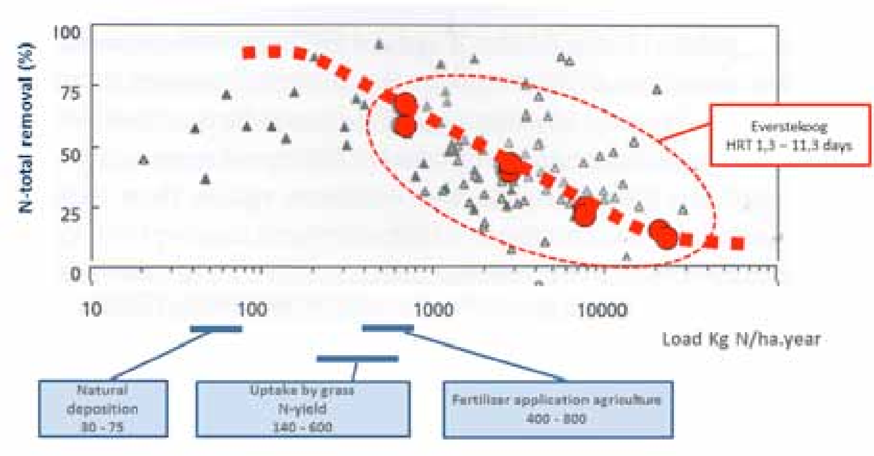


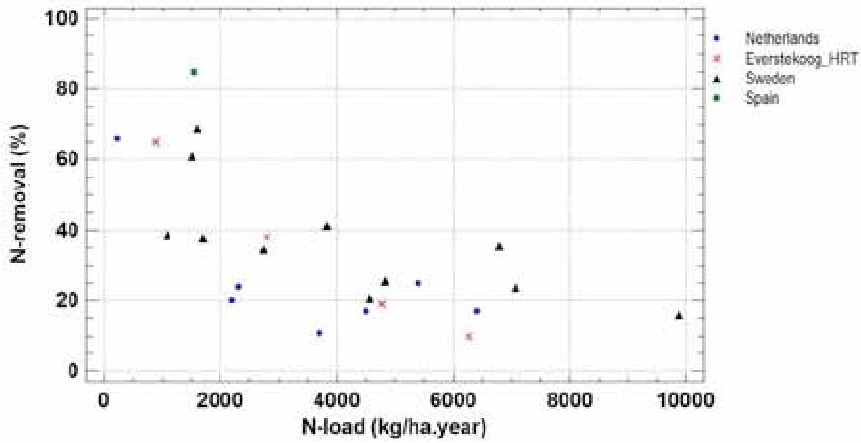
Table 3 gives the quantities and percentages removed in relation to the load for Dutch Waterharmonicas.

TABLE 3 **NITROGEN AND TOTAL PHOSPHATE REMOVAL IN SOME DUTCH WATERHARMONICA SYSTEMS**

	Total N			Total P		
	load kg/ha/year	removal kg/ha/year	removal %	load kg/ha/year	removal kg/ha/year	removal %
Aqualân Grou	2,200	430	20	340	130	38
Everstekoog	5,400	1,375	25	790	59	8
Hapert	3,700	415	11	250	-21	-8
Klaterwater/Kaatsheuvel	220	145	66	57	56	99
Land van Cuijk	6,400	1,070	17	750	16	2
Ootmarsum	2,300	560	24	649	58	9
Sint Maartensdijk	4,500	790	17	710	-272	-38

Figures 12 and 13 plot the percentage of N and P removal against the N and P removal in kg/ha/year, at Waterharmonicas in The Netherlands, Sweden and Spain (Empuriabrava).

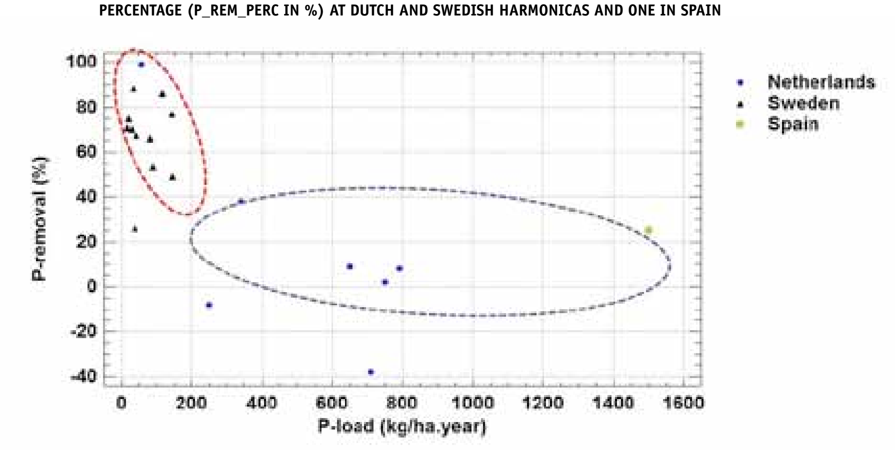
FIGURE 12 **NITROGEN LOAD (N_LOAD IN KG TOTAL N/HA/YEAR) VERSUS THE PERCENTAGE TOTAL N REMOVAL (N REMOVAL (%), AT WATERHARMONICAS IN THE NETHERLANDS, SWEDEN AND SPAIN**



A clear decrease is visible in the removal efficiency when the load increases. The total nitrogen removal in most Waterharmonica systems in The Netherlands ranges between 10-25% (blue dots). This is clearly below the results shown by Swedish systems (black triangles). De red crosses do represent the nitrogen reduction in Everstekoog during the research period with hydraulic retention times between 0.3 and 11 days (hydraulic loads of 1.4; 0.37; 0.12 and 0.04 m/day)

In some Waterharmonica systems in Sweden, nitrogen removal efficiencies of 25-50% are measured, with lower flow rates and higher concentrations (Andersson and Kallner, 2002 and Flyckt, 2010). The results at Klaterwater in the Efteling (top left of the graph) are striking. The vertical sand filter at the Kaatsheuvel STP contributes to a relatively high removal of approx. 66%. The results of the study at Everstekoog show a clear influence of the N load on the percentage removal: at long retention times and, as a result, low N loads, the removal exceeded 60 % the total N, decreasing from 5 to 1.7 mg/l). With an 80-90% removal, the Empuriabrava Waterharmonica is much more effective in retaining nitrogen than the Dutch systems, for example 82 % removal at a load of 1,550 kg N/ha/year (Sala and Kampf, 2011). The cause of these differences is not yet known. For more background and similarities between the Swedish and Dutch situations (Kampf, 2012).

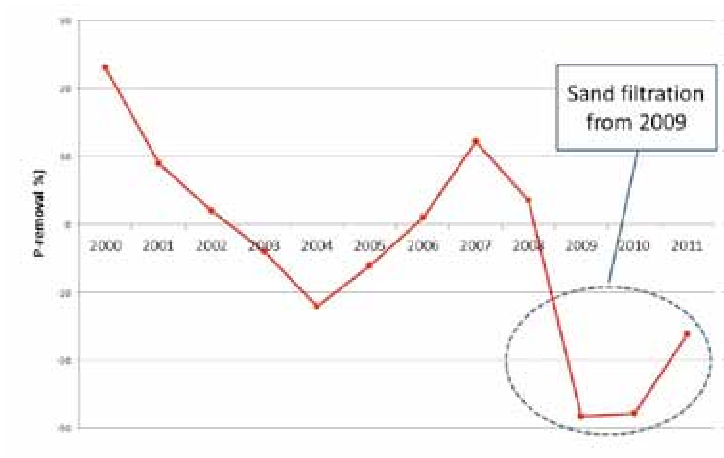
FIGURE 13 **THE PHOSPHORUS LOAD (P_LOAD IN KG TOTAL P/HA/YEAR) VERSUS THE TOTAL P REMOVAL PERCENTAGE (P_REM_PERC IN %) AT DUTCH AND SWEDISH HARMONICAS AND ONE IN SPAIN**



The phosphate removal results for Dutch Waterharmonicas (blue ellipse) are very different from those of the Swedish Waterharmonicas (red ellipse), see figure 13. In the Dutch systems, low total phosphate removals are measured in the range of -40% to +40%. Total phosphate removal largely takes place in the first settling ponds (Boomen, Kampf et al, 2012b, sub-study report 3). Moreover, the Dutch systems generally have a much higher P load. At Klaterwater, however, the combination of a sand filter (Astra filter with a fairly high dosing), a vertical reed bed through which water flows and subsequent ponds, leads to total phosphate levels of 0.01 to 0.02 mg/l and a removal efficiency of 99% (the blue dot in the upper left of the graph). In Sweden, a removal is achieved leading to values of 0.10 and even 0.06 mg P/l at lower flow rates and higher concentrations (Flyckt, 2010). The phosphorus capture in Empuriabrava is more variable. In 2010, 25 % of the supply of more than 1,500 kg P/ha/year was removed (Sala and Kampf, 2011).

The variation of P removal in the Dutch systems results from the fact that the P compounds supplied with the effluent from the STP are rather loosely bound. In the study period with retention times between 1.6 and 11 days at Everstekoog, the ortho-phosphate level decreased in the winter from 0.9 to 0.3 mg/l, a reduction of 0.6 mg/l, while in the summer, an increase from 1.3 to 2 mg/l was observed. This was confirmed at Grou and indicates P release in the sediments in the Waterharmonica during the summer months (Boomen, Kampf et al, 2012a). At the Waterharmonica symposium held on 29 March 2012, Wim van der Hulst, of Aa and Maas (in Uijterlinde, 2012), described greatly varying experiences with P removal at Land van Cuijk, see figure 14. The P removal of 20 % shortly after the construction of the Waterharmonica did not continue, even subsequently switching to P release, and ultimately reverting to P removal again. When, after 2009, the effluent from the STP ran via sand filtration (with phosphate removal), the P removal in the Waterharmonica decreased radically. It is possible that much more sludge is discharged with the effluent from the STP than is evident from the measuring results. This sludge piles up in the Waterharmonica and releases phosphate.

FIGURE 14 **PHOSPHORUS REMOVAL EFFICIENCY IN SUMMER HALF YEAR AT LAND VAN CUIJK (UIJTERLINDE, 2012)**



The long-term measuring results relating to the nutrient concentrations in the Waterharmonica systems in The Netherlands show that not only are peaks in suspended solids greatly levelled out by Waterharmonicas, but that the same also applies to peaks of nutrients (Boomen, Kampf et al, 2012b), sub-study report 4). For a measuring period of several years at Grou, for example, a maximum value of 7.3 mg P/l was measured in the output of the post-settling tank, while the maximum value in de Waterharmonica is only 1.7 mg/l. But the variation in the ratios of NH_4 and NO_3 in the overflow of the settling tank in the space of twenty-four hours is also levelled out to a large extent in the Waterharmonica. This buffering already largely takes place in the Daphnia ponds (and/or presettling ponds) (Schreijer, Kampf et al, 2000).

The fact that, in Waterharmonicas, nutrients are not seen as pollution but as a source of food in the intended food chain was already described in the report of the study carried out at Everstekoog STP (Schreijer, Kampf et al, 2000). There is, however, a problem in that the ratio between the concentration of nitrogen and phosphate is not equivalent to the 'fertiliser application recommendation for natural areas'. The study at Everstekoog did reveal that if the load is low enough (or the retention time long enough) far-reaching exhaustion of nutrients takes place. It is important to realise that:

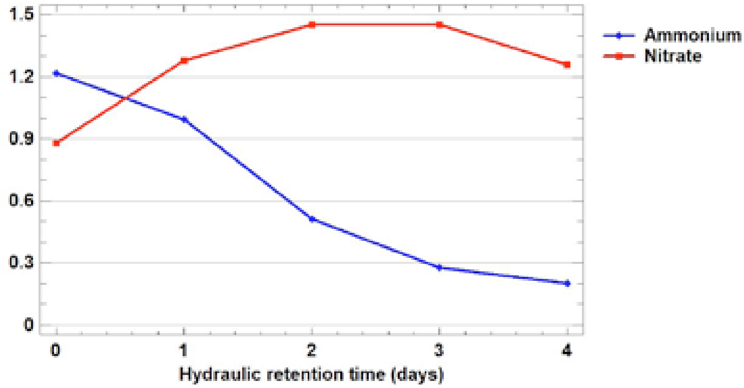
- N removal is almost exclusively a combination of storage in plants and processes in biofilms on submerged plant parts and the water bottom;
- P removal is the result of a combination of 'agriculture' and biological and chemical bonding. In many cases this bonding is not permanent. Under anaerobic conditions, phosphate compounds can break down and release phosphate. This mainly takes place when iron salts are used (for phosphate removal in the STP). There is far less subsequent supply from the sediment when aluminium salts are used (Blom and Maat, 2005 and Flyckt, 2010). Low levels of phosphates can also be achieved by capture in the sediment by adding iron salts and calcium carbonate (vertical-flow reed bed): STOWA study on phosphate removal with helophyte filters (Flyckt, 2010).

To summarise briefly, after some optimisation, a Waterharmonica can remove around 1,000 kg N/ha/year and approx. 750 kg P/ha/year with efficiency depending on the load and concentration supplied. In Waterharmonicas with a low or extremely low load (that is, a hydraulic load of less than 0.10 m/day) low N and P levels are possible. To this end, low levels of N and P must be aimed for in the STP. These levels do not have to be extremely low: we can draw the cautious conclusion that, under these circumstances, an N level of 2-3 mg/l is possible. The level of N-NO_3 will then be a practically zero. At a load of 50 to 400 kg P/ha/year, 0.4 to more than 1 mg P/l can be captured in a Waterharmonica, achieving levels of less than 0.1 mg P/l (for example, at Klaterwater).

As Klaterwater shows, low concentrations can be achieved if the supply concentrations are low. A study into natural treatment systems for the purification of drain and ditch water was carried out within the framework of the WFDInnovation programme (Haan, Sival et al, 2011). This study examined and tested surface flow wetlands for the removal of nitrate from drain water agriculture for nitrate and phosphate on a practical scale. Iron filters were used for phosphate removal, and to increase nitrate removal subsurface straw filters. These new results do not, it is true, apply to every Waterharmonica, but are useful as a framework for possibilities for increasing the nutrient removal.

Further description of possible optimisation steps falls outside the scope of this report but the study in the mesocosms at Grou, Horstermeer and Empuriabrava show fascinating results. As an example, NH_4- levels at Grou decreased in the mesocosms by 90 %, from 1.4 to 0.2 mg N/l on average, while the NO_3 concentration increased from 0.8 to 1.3 mg/l. As a result, the total N removal amounted to approx. 45%. Under the same conditions, the PO_4 decreased by almost 50 %, from 1.1 to 0.6 mg P/l. Corresponding decreases were found in mesocosms elsewhere. The precise causes are, however, not yet known and are being included in the more detailed study carried out by Ruud Kampf (figure 15).

FIGURE 15 LEVELS OF NH_4 AND NO_3 IN A SERIES OF FOUR MESOCOSMS AT GROU, EACH WITH A ONE-DAY RETENTION TIME

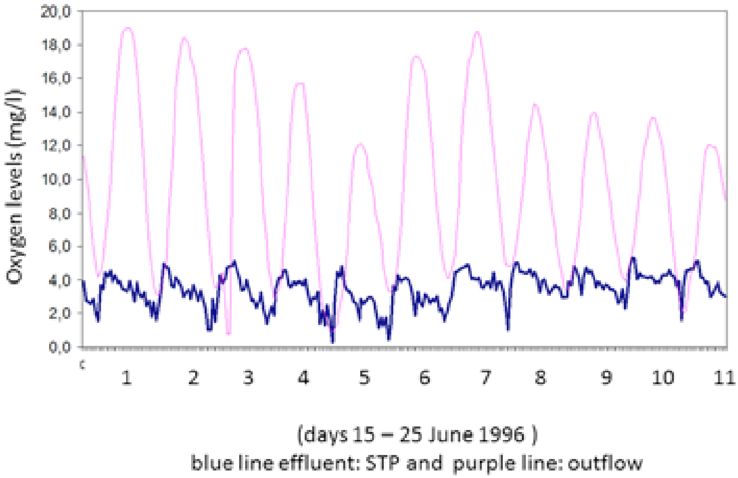


ORGANIC SUBSTANCES AND OXYGEN MANAGEMENT

Extensive research has been carried out into the oxygen management in the semi-natural system of the Waterharmonica at Everstekoog (Schreijer, Kampf et al, 2000). The primary conclusions from this study were that:

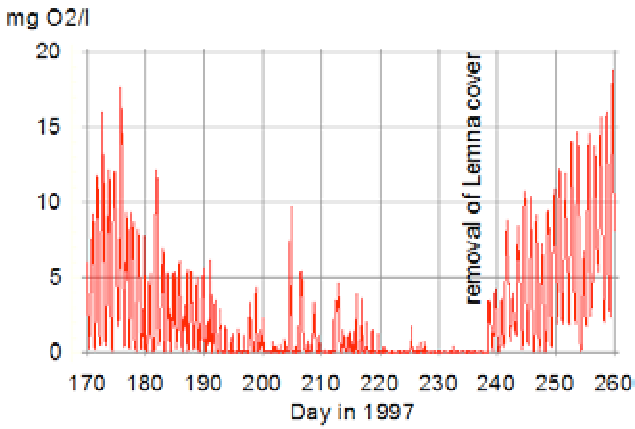
- the wetland system creates a powerful day-night rhythm in the oxygen level in the low-oxygen effluent (see figure 16);
- increasing the retention time results in a reduction of the oxygen demand so that the minimum values remain higher at the end of the night.

FIGURE 16 **THE INCREASE IN THE OXYGEN RHYTHM AT EVERSTEKOOG (OXYGEN LEVELS IN THE STP EFFLUENT ARE SHOWN IN BLUE, AND OXYGEN LEVELS IN THE WETLAND EFFLUENT ARE SHOWN IN PURPLE), FOR THE PERIOD 15-25 JUNE 1996 (SCHREIJER, KAMPF ET AL, 2000)**



- the daily oxygen rhythm is independent of the season, but the seasons do affect the amplitude;
- the oxygen production lags approx. 6 hours behind the light cycle. This is also the case on cloudy days;
- if the water is covered with duckweed, the oxygen rhythm grinds to a halt but if the duckweed cover is removed, the oxygen production rapidly recovers (see figure 17).

FIGURE 17 **REDUCTION IN THE OXYGEN RHYTHM WHEN COVERED WITH DUCKWEED AND RAPID RECOVERY WHEN THE DUCKWEED HAS BEEN REMOVED (THREE SUMMER MONTHS IN 2007) (SCHREIJER, KAMPF ET AL, 2000)**



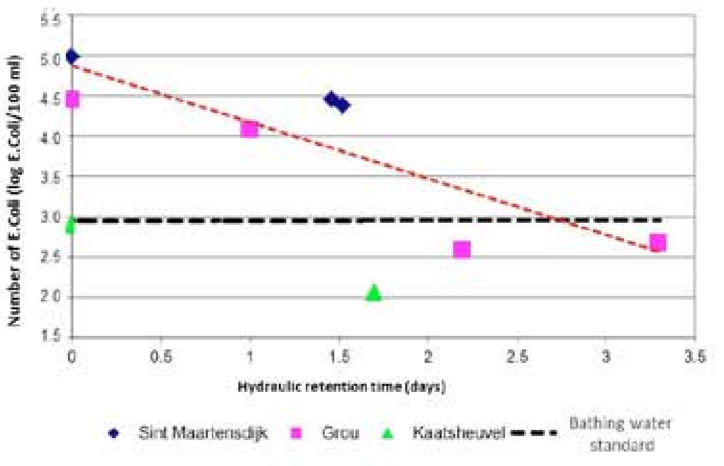
This picture was later confirmed by measurements taken at Land van Cuijk and Grou. Large reductions in oxygen demanding substances (BOD) were also measured at these sites; the extremely low oxygen levels at the beginning of the Waterharmonica increased and a day/night rhythm arose (Boomen, Kampf et al, 2012c and Boomen, 2004).

PATHOGENS

Escherichia coli *(E. coli)*, an indicator for pathogens, are presents at levels of 50,000 to 100,000 *E. coli*/100 ml in STP effluents (Boomen, Kampf et al, 2012b). There are no discharge standards for pathogens in The Netherlands. The bathing standard is 900 *E. coli*/100 ml; this is officially expressed as the Most Probable Number (MPN) which corresponds with the 'colony forming unit' (CFU). This means that if the *E. coli* values in the outlet water of the post-settling tank have to be reduced to bathing water standards at the site of discharge, a reduction of more than 98% is necessary.

Various studies have shown that a Waterharmonica results in a considerable decrease in the pathogens present. The study carried out from 1995-1998 at Everstekoog, for example, showed that a removal of 99 to 99.9% (2 log to 3 log) of *E. coli* is easily possible. An *E. coli* value of approx. 1,500 *E. coli*/100 ml was measured after the first ponds at Everstekoog, and only approx. 180 *E. coli*/100 ml after the reed ditches. The measuring results for *E. coli* at the Waterharmonicas at Sint Maartensdijk, Grou and Kaatsheuvel were recently compared (Boomen, Kampf et al, 2012c and Boomen, Kampf et al, 2012b, sub-study 4). The analysis of this multi-annual measuring series also reveals that the quantity of pathogens decreases logarithmically with the retention time. Figure 18 shows the median values of these measurements, the numbers of *E. coli*/100 ml being plotted on a logarithmic axis. This illustrates a linear decrease on a logarithmic scale.

FIGURE 18 **THE INFLUENCE OF THE HYDRAULIC RETENTION TIME ON THE NUMBER OF E. COLI (MEDIAN OF NUMBER PER 100 ML) IN THREE DUTCH WATERHARMONICAS (BOOMEN, KAMPF ET AL, 2012C). THE BLACK HORIZONTAL LINE INDICATES THE BATHING WATER STANDARD**

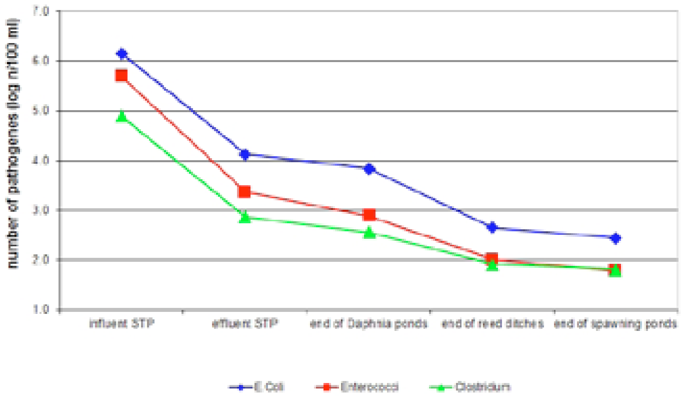


The measurements at Kaatsheuvel show a decrease comparable to that at Grou and Sint Maartensdijk which, however, starts lower because the sand filter at the Kaatsheuvel STP has already removed some of the *E. coli*. A linear relationship of log *E. coli*/100 ml = -0.69 * HRT + 4.9 can be derived from these measurements in which HRT is the hydraulic retention time. In (Schreijer Kampf et al, 2000) a link was derived of log *E. coli* = -0.65 * HRT + C. A breakdown rate of -0.65 to -0.70 is not exceptional for the dying off of *E. coli* in surface water (Ruiter, 1978).

If the *E. coli* values in the outlet water of the post-settling tank have to be reduced to bathing water standards at the site of discharge, a removal of 1.75 log is needed. In order to achieve this reduction, a minimum retention time of 2.5 day (at dry weather conditions) in the Waterharmonica is necessary. The sand filter at Kaatsheuvel also achieves these values (note: here high doses of chemicals for P-removal are applied).

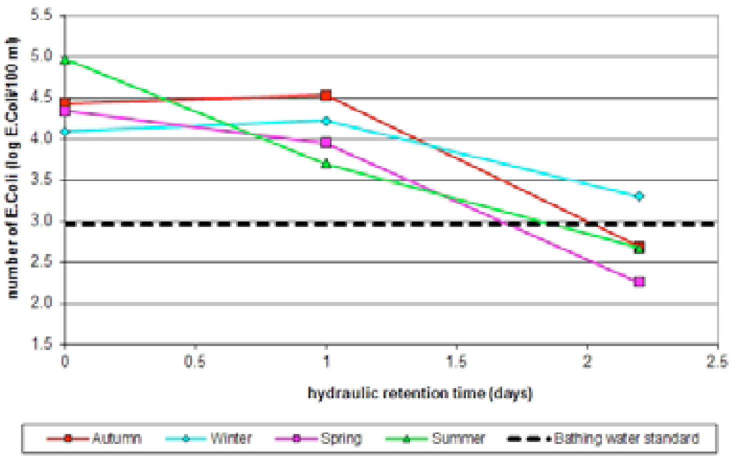
The study also shows that both the settling/Daphnia ponds and the reed ditches play an important role in the decrease of pathogens. Figure 19 illustrates the role of the ponds and the reed ditches.

FIGURE 19 **THE CHANGE IN E. COLI, ENTEROCOCCI AND CLOSTRIDIUM PERFRINGENS (NUMBER PER 100 ML) IN THE ACTIVE SLUDGE INSTALLATION AND AT AQUALÂN GROU. DATA (12 MEASUREMENTS IN 2010, STP INFLUENT SAMPLED ONLY TWICE). DATA ORIGINATING FROM THE WIPE STUDY, DERIVED FROM FOEKEMA, ROEX ET AL, 2012)**



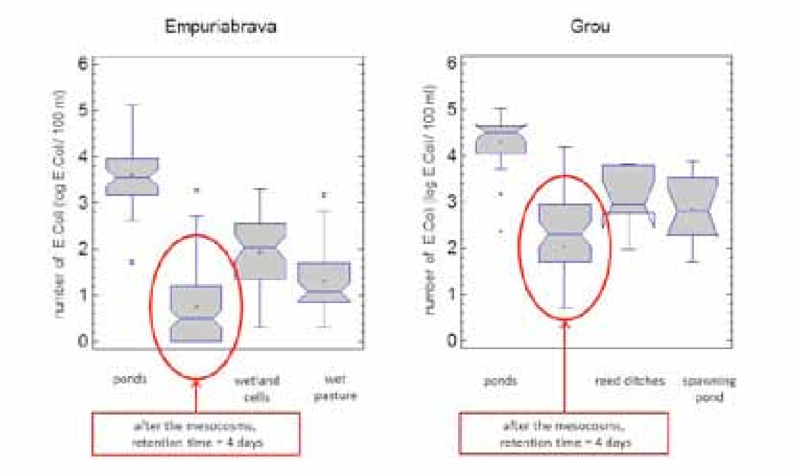
The driving processes here are probably predation by zooplankton and, to a lesser degree, death resulting from UV radiation. The pathogens do not seem to settle; they comprise many small, loose cells which are not bound to suspended solids. A clear difference has, however, been spotted between summer and winter. At Everstekoog, it was ascertained that the decrease in winter was substantially lower than that in the other seasons. At Grou, too, it was ascertained that the decrease in the summer is more substantial than in the winter, with a breakdown rate in pathogens of -1.04 and -0.36 respectively (Boomen, Kampf et al, 2012c and Boomen, Kampf et al, 2012b, sub-study 4). This is shown in figure 20. The mesocosms studies revealed that if there are sufficient Daphnia, the disinfection in the winter at temperatures below 10 degrees is not much lower than in the summer (Kampf, 2005a). In 2010, the reduction of *E.Coli* in the Daphnia ponds at Aqualân Grou is only slight, a reduction of less than a half-log. This is due to the retention time in these ponds being too short and the (resulting) low numbers of Daphnia at Grou. See also figures 20 and 21.

FIGURE 20 **THE INFLUENCE OF THE HYDRAULIC RETENTION TIME ON E. COLI LEVELS (NUMBER/100 ML) IN THE DIFFERENT SEASONS AT AQUALÂN GROU (BOOMEN, KAMPF ET AL, 2012C). THE DOTTED LINE INDICATES THE BATHING WATER STANDARD)**



The studies carried out in the mesocosms also show that a further process optimisation is possible, see figure 21.

FIGURE 21 **THE NUMBERS OF E. COLI (NUMBER/100 ML) IN THE MESOCOSMS (IN THE RED CIRCLES) AT EMPURIABRAVA AND GROU IN RELATION TO THE WATERHARMONICA COMPONENTS (KAMPF AND SALA, 2009). FOR MORE INFORMATION ABOUT THE BOX-WHISKER PLOTS, SEE BOOMEN, KAMPF ET AL, 2012B)**



Why the results for pathogen removal are so much better in the mesocosms is not clear yet. Possible causes are higher predation by Daphnia and more undisturbed flocculation and settling of sludge particles in the mesocosms, and less hydraulic short cuts. There may also be less contamination of the mesocosms by birds than in the field. On-going research on suspended solids and filtration by Daphnia (and other Cladocera) proof that in the mesocosms of Empuriabrava Daphnia do indeed improved the water quality of wastewater reducing the particle volume concentration of small particles, which are the most difficult to remove from wastewater, promising results for tertiary treatment and wastewater reuse based on the filtering capacity of “Daphnia” (Pau, Serra et al, 2013).

The aforementioned examples have shown the importance of the hydraulic retention time (figure 18) and that short-circuiting currents lower the average retention time. After all, at Aqualân Grou, this is not 5.6 days as intended in the design, but only 3 days (Boomen, Kampf et al, 2012c, sub-study 2). Possible preferential currents and dead zones, which contribute little to the purification result, are also seen in other

Waterharmonicas, such as the three ‘wetland cells’ at Empuriabrava, left on photo 7. Here the water flows between islands overgrown with vegetation. The retention time of the water at Ootmarsum also seems to be much shorter than planned in the design.

PHOTO 7 **THE EMPURIABRAVA WATERHARMONICA, SPAIN**

‘Biological’ disinfection can certainly compete with ‘chemical’ disinfection. A comparison between the results measured at Everstekoog and Wervershoof during the summer season of 1996 is cited to support this (Kampf, Schreijer et al, 1997). Average values of 2,700/100 ml were measured for *E. coli* at Everstekoog (HRT 2 days) that summer. This is clearly lower than the 11,100/100 ml measured during the same period at Wervershoof where chemical disinfection with sodium hypochlorite was carried out. The process stability after the Waterharmonica at Everstekoog was also better (median values 220/100 ml and 800/100 ml respectively).

ECOTOXICOLOGY AND XENOBIOTIC SUBSTANCES

The water discharged from the post-settling tank of an STP can contain various bioaccumulating or toxic substances. These substances can affect the ecological working of a Waterharmonica by accumulating in the food chain. It is, furthermore, important to establish whether anything happens to these substances in a Waterharmonica so that cleaner water is discharged.

At the Everstekoog system, during the period 1995-1998, it was ascertained that heavy metals remained behind in the Waterharmonica by sedimentation and possible filtration of the fine suspended solids by Daphnia. In 2000, it was further ascertained that, although the discharge of STP effluent to the surface water cannot have acute toxic effects, it can have chronic toxic effects (Berbee, Naber et al, 2000, Berbee, Maas et al, 2001). The STOWA study carried out in 2003 into the ecotoxicological effects in relation to biomass culture (Blankendaal, Foekema et al, 2003) describes that the effluent from STPs can have an inhibiting effect on algae development, but not on that of Daphnia. Later a negative relationship was found between the phosphate level of the effluent and the inhibition of the algae growth as a result of which the negative relationship with the presence of toxic substances became weaker (Slijkerman, Dokkum et al, 2006). Some bio-accumulation was found; this was high in the case of STPs with excessive loads and less dominant in the case of STPs with lower loads (Blankendaal, Foekema et al, 2003).
The WFD Innovation project WIPE (Foekema, Roex et al, 2012) looked even more specifically into the effects and relationships with effluent quality in the Waterharmonica. To this end, use was made of passive samplers (so that substances could be analysed at low concentrations), various types of bioassays, microbiological research and biological and biomarker (gene expression) research on fish (sticklebacks) subject to chronic exposure at sites. The Waterharmonicas examined (Grou, Land van Cuijk and Hapert) appeared to have a favourable effect on the toxicological and bacteriological quality of water from the outlet of the post-settling tank. No indications were found of risks of acute toxicity.
However, a high mortality was ascertained within a relatively short period among the sticklebacks exposed in one of the Waterharmonicas. The cause was not traced, but was evidently removed by the Waterharmonica because, at the end of the Waterharmonica, the survival of the fish was normal. No increased mortality was ascertained at any of the sites in the rest of the exposure period of more than a year,

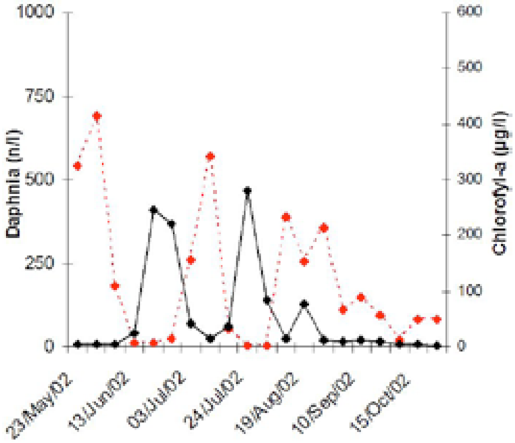
which emphasises the fact that the above-mentioned mortality was incidental. Moreover, no deformed sticklebacks were found. Toxicity levels were, however, exceeded, whereby effects could arise on chronic exposure. In these periods, a raised level of pesticides/herbicides was ascertained in the effluent in many cases. On passage through the Waterharmonica, this toxicity decreased, which corresponds with a decrease in the calculated environmental risk on the basis of the concentration of pesticides/herbicides. The oestrogen (endocrine disrupting) activity of the effluent/sediment also decreases in the Waterharmonica. Microbiological research has shown that water/sludge mixtures from Waterharmonicas have a strong potential for breaking down oestrogenic substances. Although, in practice, oxygen deficiency probably forms the limiting factor for the optimum break down of these substances, the fish showed fewer indications of endocrine disruption the closer to the end of the Waterharmonica they were exposed. The indications of endocrine disruption ascertained only involved individual fish. The reproductive success of the exposed group was not affected by this (Foekema, Roex et al, 2012).
To summarise, we can conclude that the water from the outlet of the post-settling tank of STPs usually causes few toxic effects, but can cause incidental risks. The exotoxicological risk decreases along the course of the Waterharmonica system (Foekema, Roex et al, 2012). This is partly the result of the lowering of the risk of high ammonia levels in periods of insufficient nitrification in the STP because these peaks are strongly buffered. Furthermore, a Waterharmonica does not raise the ecotoxicological risk with added chemicals and/or breakdown products, unlike other 'fourth-step treatments' (after ozone dosing or UV treatment, for example). These findings do not contrast with the results in Empuriabrava (Matamores, Bayona et al, 2010).

ECOLOGY

There is only fragmented information available on the ecological value of Waterharmonicas. There has been continual attention for ecological aspects and particularly for the lower organisms such as algae and Daphnia, but this has not been structurally incorporated in the monitoring and reports. The summary of the report of the study carried out at Everstekoog (Schreijer, Kampf et al, 2000), for example, only mentions that the Waterharmonica 'produces a robust oxygen rhythm with high over-saturation during the day and a short low-oxygen period at night. The oxygen rhythm is well suited to the situation in the receiving surface water'.

The quantity of algae in a Waterharmonica, and particularly in the first pond(s), is limited by the grazing by Daphnia. During a test at Everstekoog in a test pond with a fairly long retention time of 4.5 days, there were two peaks immediately after the Daphnia population collapsed (figure 22). In both cases the population recovered quickly (Kampf, 2005c).

FIGURE 22 **INFLUENCE OF DAPHNIA (RED LINE) ON THE OCCURRENCE OF ALGAE IN TEST PONDS AT EVERSTEKOOG, EXPRESSED AS THE LEVEL OF CHLOROPHYLL A (BLACK LINE). THE RETENTION TIME OF 4.5 DAYS IS FAIRLY LONG FOR A SINGLE POND (KAMPF, 2005C)**



At Everstekoog (Schreijer, Kampf et al, 2000), the dominant aquatic plant species in the ditches are primarily western waterweed, prickly hornwort, common duckweed (lesser duckweed), fennel pond weed, lesser pondweed, fat duckweed and curly pondweed. A microbial community, consisting of (mostly one-celled) algae, bacteria and fungi, develops on hard surfaces and the water bottom. This microbial community, along with any organic substances and fauna present, is termed 'periphyton'. In the helophyte vegetation, the periphyton on the water bottom is dominated by diatoms and flagellates (<10 μm), with large numbers of blue and green algae. Diatoms dominated at the bases of the helophyte stems whereas, in the spring, green algae were more significant because of the high incident light and in the autumn the flagellates took over. A year after the construction of the filter, there were large numbers of Daphnia (up to approx. 300/l) in the presettling basin in the six summer months. The majority (70%) of these Daphnia belonged to the genus Daphnia (*Daphnia magna* and *Daphnia pulex*). The high densities are maintained because of the absence of predators in the presettling basin. The macrofauna were dominated by mosquito larvae, snails and chaetopod worms. Fish were hardly present between 1995 and 1998 but some sticklebacks were found in the ditches later. There were still no fish in the presettling basin in 1999. Test fishing by George Wintermans showed numbers up to 15 per m^2 out in the ditches with a retention time of 3 days or more. Handfuls of sticklebacks were often present in the dams at Everstekoog (photo 8).

Incidentally, it takes at least a year for a Waterharmonica to become 'biologically stable' after construction. At Everstekoog, all the electrodes in the system were covered with eggs of aquatic heteropteran bugs (Schreijer, Kampf et al, 2000). There was a great deal of filamentous algae (e.g. Spirogyra) and duckweed growth at Grou in the first year (Boomen, Kampf et al, 2012a), and subsequently much less.

PHOTO 8 **THERE WERE OFTEN LARGE NUMBERS OF TEN-SPINED STICKLEBACKS IN THE WATERHARMONICA AT EVERSTEKOOG, PARTICULARLY IN THE DAMS BETWEEN THE PRESETTLING POND AND THE DITCHES (PHOTO: RUUD KAMPF)**

Fish surveys were carried out *yearly* at Aqualân Grou in 2008 through 2012 (Claassen and Koopmans, 2012). In the early years, the Daphnia ponds remained free from fish and sticklebacks were only found in the reed ditches. In the spawning pond at Grou, the number and diversity of fish has increased greatly since the construction, so that it now supplements stocks in the Frisian *'boezem'* (Frisian basin water system). Table 4 shows the number and species of fish in the fish spawning pond at Grou.

TABLE 4 **LIST OF THE NUMBERS OF FISH CAUGHT AND THE PERCENTAGE OF THESE NUMBERS WITH BROOD PER YEAR (JULY 2008, SEPTEMBER 2009, AUGUST 2010, SEPTEMBER 2011, SEPTEMBER 2012) IN THE SPAWNING BIOTOPE OF GROU (CLAASSEN AND KOOPMANS, 2012)**
(+) INDICATES FISH SPECIES PRESENT IN APRIL 2011, BUT NOT IN SEPTEMBER 2011

	2008		2009		2010		2011		2012	
	n	% brood	n	% brood	n	% brood	n	% brood	n	% brood
Perch	9	22	102	81	112	76	126	81	32	56
Roach	54	67	75	56	41	54	116	57	73	5
European Bitterling	-	-	14	14	7	29	18	100	1	100
Bream	2	0	-	-	-	-	-	-	-	-
Three-spined stickleback	1	100	1	100	-	-	1	100	-	-
Gibel carp	2	100	-	-	-	-	1	100	-	-
Spined loach	4	0	10	0	1	0	-	-	5	0
White bream	2	50	13	85	5	100	47	100	7	100
Eel	2	0	4	0	1	0	(+)	-	-	-
Ruffe	1	100	4	25	13	77	(+)	-	-	-
Gudgeon	6	33	46	43	44	87	1	100	-	-
Rudd	6	0	3	100	24	88	6	17	3	33
Pike	3	100	2	0	6	17	6	50	8	100
Ten-spined stickleback	1	100	1	100	-	-	(+)	-	1	100
Belica	-	-	1	100	-	-	-	-	2	100
Tench	5	40	4	100	2	50	3	67	4	50
Total	98	52	288	58	256	72	325	74	136	32
Number of species /	14		14		11		10		10	
Percentage of species with brood	14	10	14	11	11	9	10 (+3)	10	10	9

The fish surveys in Grou show the value of the fish spawning pond at the end of a Waterharmonica, for both local nature development (semi-natural fish nursery) and as a contribution to a more balanced eco-system in the large Frisian basin water system (Claassen and Koopmans, 2012).

After a few years, however, large numbers of ten-spined sticklebacks could also be found in the Daphnia ponds at Grou, which were intentionally kept as free from fish as possible. In order to maintain high numbers of Daphnia (and other zooplankton) in Daphnia ponds, the fish population has to be kept down. This can be achieved by a technical setup whereby the aquatic plants (which are important for the reproduction of the ten-spined stickleback) do not get the chance to grow, by biological management of the fish population by removing some fish and/or setting out young pike (as predators of the sticklebacks) or by allowing high concentrations of NH_4 into the ponds now and again (so that there is a selection of the larger, stronger *Daphnia magna*).

There are striking numbers of frogs at Aqualân (Boomen, Kampf et al, 2012a).

All Waterharmonicas are attractive for birds. Breeding birds in Everstekoog were for example tufted duck, shoveller, mallard, gadwall, mute swan, common gull, oystercatcher, redshank, coot, moorhen, yellow wagtail and reed warbler (Schreijer, Kampf et al, 2000). Spoonbills and Kingfishers were attracted by the high numbers of sticklebacks. Photo 9 is a collage from the Waterharmonica at Empuriabrava, Spain. Waterharmonicas appear to attract a large variation of birds, the site www.waarneming.nl gives a fine overview. The observations in the Waterharmonicas can be consulted through (Stichting Natuurinformatie, 2013): www.waterharmonica.nl/vogels. The longest series of counts is in Tilburg-Noord. The largest variation is in Kristalbad, with on 2012 alone, in total 141 different bird species, like smew, ferruginous duck, great white egret, spotted crake, etc..

PHOTO 9 PHOTO COLLAGE OF BIRDS AT EMPURIABRAVA, SPAIN (PHOTOS BY RUUD KAMPF)

A field study carried out by the UvA in 2006 in the framework of 'student project weeks' (Kalshoven, Scheltes et al, 2006) at the Waterharmonica at Everstekoog has shown that the biodiversity in the Waterharmonica is increasing significantly. This is clear from the numbers of species present, but less so from biotic indices because the latter do not illustrate the water qualities as well. The improvement of biodiversity can be ascertained from both the number of species and a shift to 'clean water species'. The hydraulic retention time also plays a significant role in these surveys: a positive effect was only detected after a retention time of 3 days. Research carried out in 2008 at Grou (Brink and et al, 2008) yielded corresponding findings.

Despite the fact that there has not been any extensive structural monitoring of the ecological value in Dutch Waterharmonicas, the various studies, including that carried out in Spain, show that nature is being created. This nature is not usually the type one can get lyrical about (Boomen, 2004), but the Waterharmonica does contribute to biodiversity. In doing so, it forms a good transition from the Water Chain to the Water System.

7

WHAT DOES A WATERHARMONICA YIELD APART FROM NATURE, RECREATION AND WATER BUFFERING?

A Waterharmonica has a purifying effect and can, therefore, transform water which has been technically treated into more natural water. However, there is more to be won by constructing Waterharmonicas. They can, for example, be used to explain the cycle of Water Chain and Water System to administrators, public and pupils. There is a role for the water authorities here. This education can take place using information boards (like those erected at the Grou STP, see photo 10) or by arranging excursions for groups as often takes place at Land van Cuijk STP. At Grou, special programmes have been developed for both pre-vocational secondary education and for practical research for trainees).

This education can easily be linked to recreation. The areas are eminently suitable for walks. Trails have been laid out at the Waterharmonicas at Aqualân Grou, the Waterpark Groote Beerze in Hapert, Ootmarsum, Sint-Oedenrode, Soerendonk and Kristalbad. In all these cases, the Waterharmonica is freely accessible, although the STP is not open to the public. Direct contact with the water must not be stimulated because the water may not be hygienic reliable. Incidentally, this rather extensive recreation goes well with natural values and resting areas for birds can be created. Visitors' perceptions of nature at Sint-Oedenrode and the Kristalbad are enhanced by showing them the area from watch towers. The Waterharmonica is not expected to result in high natural value but the clear Water System with its diversity of plants does attract many birds and other animals. Despite concerns, problems with mosquitoes have never been ascertained at existing Waterharmonicas. For more information about how the public view the Waterharmonicas at Regge en Dinkel and De Dommel, see (Regge en Dinkel, 2011b) and (De Dommel, 2012b, De Dommel, 2012c and Zanten, 2012) respectively.

PHOTO 10 INFORMATION BOARD AT AQUALÂN GROU (PHOTO BY RUUD KAMPF)

In the design of the Waterharmonica at Biest-Houtakker (De Dommel, 2011b), Waterschap De Dommel indicates that it wants to raise its profile by means of this STP: *'The site has been landscaped in such a way that the STP is no longer hidden as it used to be. We feel that it should stand out and be visible to everyone. We are proud of the attractive building complex and proud of what is achieved here. De Reusel is once more a wonderful stream to fish in and walk along'.*

8

WHAT DOES A WATERHARMONICA COST?

The costs of a Waterharmonica have to be divided into its construction costs (investment costs) and management and maintenance costs (operating costs). The investment costs are first looked at below.

An important precondition in the construction of a Waterharmonica is the availability of land near the STP. Where will this land come from? Is it the property of the water authority? It can also be contributed by third parties, such as nature managers and municipalities. The Waterharmonica does not, in fact, have to be laid out on the land owned by the water authority and does not have to be adjacent to the water treatment plant either (as is the case at Klaterwater). By combining functions, e.g. landscape reconstruction or water buffering (Kristalbad), other financial sources can also be deployed and the extra costs of a Waterharmonica can be kept down.

Besides the cost of the land, the primary costs relate to the construction of the ponds, reed ditches and banks with a few linking structures. Based on the costs of construction of the Waterharmonicas discussed earlier, rough costs for more complex Waterharmonicas (such as Everstekoog, Grou, Land van Cuijk and Soerendonk) can be estimated at approx. €175,000 per hectare (price level 2012). The cost of simpler systems (such as Sint Maartensdijk) can be kept down to approx. €75,000 per hectare. Additional specific costs such as those for relocation of sewage lines, the option of an extra vertical sand filter or a vertical flow constructed wetland, or the construction of recreational facilities, can raise these construction costs to € 200,000 - 250,000 per hectare. This is often related to the high requirements concerning nutrient or pathogen removal. Table 5 lists some of the characteristics of the prominent Waterharmonicas. The average construction costs of Swedish Waterharmonicas are approx. € 150,000 per hectare.

TABLE 5 INVESTMENT COSTS OF WATERHARMONICA SYSTEMS IN THE NETHERLANDS

	Not indexed			Indexed to 2012		
	price level	investment	index	per netto hectare	per bruto hectare	per p.e.
		€		€/ha	€/ha	€/p.e.
Elburg	1977	200,000	1.75	23,500	15,500	2.20
Everstekoog	1994	245,000	1.33	251,500	121,000	11.65
Land van Cuijk	2000	600,000	1.17	179,500	91,000	10.30
Grou	2006	175,000	1.08	214,000	145,000	23.55
Hapert	2001	575,000	1.17	176,500	129,000	11.65
Klaterwater	1997	1,039,000	1.33	194,500		125.45
The Kristalbad	2012	5,056,000	1.00	235,000	126,000	18.38
Maartensdijk	2000	53,000	1.17	62,000	13,000	3.20
Ootmarsum	2008	250,000	1.08	117,000	61,000	11.10
Raalte [1]	2009	2,400,000				
Sint Oedenrode [2]	2011	650,000	1.03			
Soerendonk	2010	1,690,000	1.03	435,000	256,000	41.45
Tilburg-Moerenburg [3]	2012	1,800,000	1	660,000	475,000	N/A
Tilburg-Noord	1996	400,000	1.33	22,000	25,000	1.42
Vollenhove	2012	100,000	1	100,000	83,000	6.30

Re 1: The construction of Raalte was postponed, estimated costs from Ott, Blom et al, 2009.

Re 2: Sint Oedenrode was constructed as compensation for landscape degradation; the costs include the construction of a watchtower, a work of art and a pedestrian bridge with dams.

Re 3: Tilburg-Moerenburg is not a Waterharmonica for the post-treatment of effluent, but a 'storm Waterharmonica' for the buffering and purification of rainwater discharge for the Tilburg-Noord STP. The investment shown is only for the expansion of phase 2 (2.73 ha wet surface area on 3.78 ha land).

The management, including basic monitoring, costs an average of approx. € 7,500/ha/year. The costs range from € 3,000/ha/year for the systems comprising several hectares, such as the Kristalbad, to € 25,000/ha/year for smaller systems, such as Soerendonk and Grou. This amount depends on the extent of the monitoring (from basic to research-oriented monitoring) and the surface area of the Waterharmonica. Management and maintenance costs for Swedish Waterharmonica systems vary between € 1,000 and € 7,000/ha/year.

Maintenance consists primarily of the annual or biennial mowing of the reed and the dredging and removal of aquatic plants. Sludge and any contaminants present tend to accumulate (Everstekoog, Grou, Land van Cuijk) and it is best if this material is collected in ponds that are easily accessible. The development of vegetation and the future loads at the Kristalbad have not yet sufficiently crystallised out to be able to draw any conclusions about the sludge accretion in the system. A multi-annual monitoring programme will provide answers in the future. The only energy used by Waterharmonicas, if at all, is that required for pumping, as is the case at Grou and Klaterwater (Baltussen, 2011, Sala and Serra, 2004)

For comparison, an indication can be given of the costs of a Waterharmonica and alternative purification technologies such as sand filters, UV installations, etc. Indicative capitalised costs of investment, management and maintenance are given below in € per m^3 of treated waste water on the basis of various STOWA reports (Jong, Kramer et al, 2008):

- STP, basic treatment approx. € 1.00/m^3
- Ultrafiltration approx. € 0.35/m^3
- UV disinfection (pathogens) approx. € 0.20/m^3
- Coagulation and (bio)filtration (N and P) approx. € 0.20/m^3
- Slow Sand filter (Leidsche Rijn) approx. € 0.10/m^3
- Waterharmonica approx. € 0.05/m^3

All in all, a Waterharmonica therefore increases the costs of the purification of waste water (approx. € 1 per m^3 of treated water) by an average of € 0.05 per m^3 of treated water, with a range from € 0.02/m^3 to € 0.12/ m^3.

A Waterharmonica yields benefits in return for these costs. These are social benefits which technical solutions do not generally have, such as the conversion of 'dead water' to 'living water' (increasing biodiversity), the balancing of peaks in concentrations of substances, natural disinfection which does not require chemicals or consume energy, and a recreational area which can be used for education (about nature). Combinations of functions are possible such as water storage, combating desiccation, nature, recreation and biomass production. These benefits are difficult to quantify. What is the value of 'living water'? How does one put a value on the feelings of a recreational 'user' if he or she sees a spoonbill foraging in a Waterharmonica or a bittern flying away or of a fisherman who knows that there are many different fish species in a spawning pond? This has been a puzzle since a long time (Knight, Clarke et al, 2004 and Kampf, Eenkhoorn et al, 2003). It is usually only possible to calculate these benefits indirectly. The importance of 'man-made nature' for water managers is evident from the attention paid to websites, for example, that of the Amsterdamse Waterleidingduinen (Amsterdam drinking water supply) entitled 'Waternet' (Waternet, 2012). In England, Anglian Water, for example, pays a great deal of attention to the recreational co-use of drinking water reservoirs; the number of visitors exceeds 2 million annually (Anglian Water, 2012, Anglian Water, 2011). Here, too, the benefits are difficult to assess, although especially the reintroduction of ospreys in Rutland has attracted a lot of interest. Anglian Water, 2011 indicates that for 2005 'it is estimated that £154,000 of visitor spending in the local area is attributable to the presence of the ospreys'. The possible value of a larger Waterharmonica is illustrated by Parc du Marquenterre in the delta of the River Somme on the French coast. This area has a design similar to a Waterharmonica with a low load which focuses partly on nature and recreation. The number of visitors annually exceeds 150,000 by far; the admission fee is €10.50 per day NN, 2012b.

Can costs which have been avoided be deemed revenues? This criterion can be estimated, reasoning from the point of view of the STP, but also from that of the management of surface water and nature management. For several impressions (Kampf, 2012 and Kampf and Boomen, 2013):

- calculated from the standpoint of the STP, approx. 40 kg N and 2 kg P are discharged per population equivalent per year. At a treatment fee of €80 per population equivalent per year and an equal distribution of costs (over N and P) that comes down to €1 and €20 per kg nitrogen or phosphorus removed respectively;
- if, as a result of the construction of a Waterharmonica, no supplementary technology is required to remove pathogens (e.g. UV disinfection), the costs avoided amount to €0.20/m^3;
- the STOWA study 'Moerasbufferstroken langs watergangen; haalbaarheid en functionaliteit in Nederland {Wetland buffer strips along waterways; feasibility and functionality in The Netherlands }' (Antheunisse, Hefting et al, 2008) indicates, on the basis of research carried out by the Ministry of Agriculture, Nature and Food Quality (LNV) in 2006, that the 'costs avoided' per kg of nitrogen removed amount to between €1.33 and €2.20, and for phosphorus €8.50;
- the WFD study 'Natuurlijke zuiveringssystemen {Natural purification systems}' (Haan, Sival et al, 2011) concludes that the costs per kilo of nitrogen and phosphorus removed were €5 to €40 and €115 respectively;
- it is interesting to note that, in the same report, because of the retention of the water, the cost of €3.50/m^3 for the water storage is avoided. This means that an amount of €350,000 of 'avoided costs' can be assumed for the retention of 100,000 m^3 in a Waterharmonica.

9

MANAGEMENT AND MAINTENANCE

As is the case with the Water Chain and the Water System, a Waterharmonica requires management and maintenance, although these costs are considerably lower than the high process control and energy costs of the STP itself. The costs of a Waterharmonica are, however, higher than those of surface water management because of the higher nutritional value of the water. The costs and requisite efforts for management and maintenance are highest at the beginning of a Waterharmonica and they decrease along its course. Conversely, the natural values increase from the beginning to the end of the Waterharmonica. This has been visualised in figure 23, on the basis of the configuration of the Waterharmonicas at Everstekoog, Grou and Soerendonk (Kampf and Sala, 2009).

FIGURE 23 **INVERSE RELATIONSHIP OF MANAGEMENT AND MAINTENANCE VERSUS NATURAL VALUE (KAMPF AND SALA, 2009**

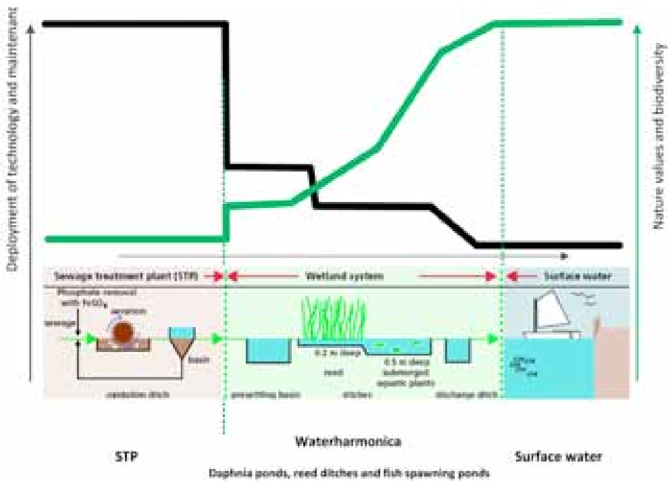


Figure 23 shows that the STP is the most expensive part of the system and that it has the least natural value. The Daphnia ponds, which still have a limited natural value, are much cheaper, but require considerable management, relatively speaking. This management comprises the removal of accumulated sludge, aquatic plants, filamentous algae and so on. In terms of natural value and management, reed ditches can be compared with naturally structured polder ditches, and are therefore not expensive but do have a fair amount of natural value. Finally, once the effluent has been changed into 'usable surface water', the natural values increase substantially, particularly if this last part is constructed in the form of a spawning pond (Grou, Soerendonk) or as a marshy pasture (Empuriabrava).

PHOTO 11 **DRAINING THE DAPHNIA PONDS AT EMPURIABRAVA (PHOTO BY RUUD KAMPF)**

The captured sludge particles originating from the STP require additional attention. An old TNO study shows that reeds are eminently suitable for capturing and transforming active sludge, as well as natural sludge, under water, too (Kampf, 1983). In such a case, it is not necessary to remove the sludge frequently. The reed bed rises slowly and the sludge is extensively aerobically stabilised. The situation is different for the settling of sludge in the (Daphnia) ponds. In the latter, a lot of sludge settles, as has been established in the systems at Empuriabrava, Everstekoog, Land van Cuijk and Grou. This sludge can be removed regularly (preferably from engineered ponds) or it can be reduced by draining the 'natural' ponds now and then (see photo 11). What is more, the draining helps prevent the release of phosphate in the ponds.

Whether those responsible for the surface water or those that manage the treatment should implement the management and maintenance of the Waterharmonica is also under discussion. The Waterharmonica is often seen as an extension of the STP and is, therefore, included in the site management and maintenance. Dutch Waterharmonicas are usually managed by the water managers. It may be advisable to locate Waterharmonicas on the sites of a neighbouring farmer or nature manager who is subsequently recompensed, according to agricultural standards, for the maintenance and management of the Waterharmonica. The farmer would then become a water farmer or water manager (Clevering, Oppendijk van Veen et al, 2006); see also (Eekeren, Verwer et al, 2012). Waterschap Regge en Dinkel has chosen to contract out the management and maintenance of the Kristalbad site to provincial nature organisation Landschap Overijssel, the maintenance of the engineering works stays a task of the water authority.

To summarise: the management and maintenance efforts chiefly consist of the removal of vegetation and reeds, dredging, re-profiling and, if necessary, redevelopment after an unknown period of time (e.g. replanting reed ditches). In this sense, the management of Waterharmonicas is not fundamentally different from the management of storage basin land or other wet areas.

10

DESIGN GUIDELINES

The design (layout, dimensions and load) of Waterharmonicas depends on their intended functions, although, in fact, combinations of all kinds of layouts and landscaping are desirable.

The sequence used at Everstekoog, Land van Cuijk and Grou, with a settling pond first, followed by a reed bed and finally an aquatic Daphnia pond which can also serve as a spawning biotope for fish, has proven functional. The actual retention time appeared shorter in these systems than the design retention time due to the presence of shortcut currents. Moreover, the dimensions of various components appeared to be smaller than laid down in the design. At both Everstekoog and Grou, this was because of the very muddy situation during construction and the unstable soil at Grou also led to caving in of banks. Therefore the banks around the Daphnia ponds were reinforced in 2011. This fits in with the idea behind figure 23, with its more technical layout of the Daphnia ponds, constructed with simple wooden camp - shot (in Grou vertical piles) or even in a concrete construction to simplify management. A few aspects here are the removal of accumulated sludge (including preventing the release of phosphorus), management (removal of filamentous algae) and optimisation of the Daphnia population (it is possible to create a more stable population by harvesting approx. 20% of the population per day (Kampf, Geest et al, 2007, Rosenkranz, 2001). The reed system after the first pond then forms the transition to a more natural system. It can be constructed as ditches for easy maintenance or in more natural forms for more bio-diversity.

An idea which has not yet been tested is to return some of the oxygen-rich water from the last aquatic plant pond to the beginning of the reed ditches to optimise the nitrification and denitrification process.

The main functions are differentiated below (see also table 6).

- **THE REMOVAL OF SUSPENDED SOLIDS AND PATHOGENS**
  The best way to achieve this is to lay the first part of the Waterharmonica out as a system of ponds of sufficient dimensions. A hydraulic retention time of at least 3 days in the ponds is advised, this can also take place in deeper ponds (Waterharmonica with medium to high loads: load 0.1 - 0.3 m/day). It is also advisable to design these ponds such that the sludge can be removed easily. The sludge must be removed because the pathogens which have sunk together with the sludge particles only die slowly under anaerobic conditions and can churn up and re-enter the water phase. The ponds also serve as a plug flow to prevent algae blooms and short-circuiting currents.

- **NUTRIENT REMOVAL**
  Nutrient removal should largely take place in the STP (biological N and P removal) or via successive flocculation (with sand filtration). The Waterharmonica then lowers the remaining N and P effectively. Natural systems are, in fact, good at removing these types of residual concentrations. For ammonium removal, an oxygen-rich phase is desired in the ponds, after which the nitrate formed becomes available for growth or is lost via denitrification (in reed ditches). Removal in a Waterharmonica depends on the concentration and decreases the greater the load. It is also important whether the nitrogen is in the form of ammonium or nitrate. The same applies to phosphate. Limited additional P-removal can take place in (Daphnia) ponds or reed beds or a vertical reed filter linked between (such as that at Klaterwater). It is better to use Al salts instead of Fe salts as flocculant for P removal because, just like biologically captured phosphorus, iron phosphates are less stable under anoxic and anaerobic conditions and the captured P

compounds can dissolve into the water again. A Waterharmonica with a low to an extremely low load (< 0.1 m/day) is required for acceptable nutrient removal.

- **NATURAL AND RECREATIONAL VALUES**

  The type of nature required must first be established: a nutrient-rich habitat with many individuals and few species or a nutrient-poor habitat with greater biodiversity. Subsequently, the choice can be made as to whether it should be an environment rich in aquatic plants, in reed zones with reed birds, a swamp forest and/or in fish spawning areas (see figure 23). The biodiversity increases along the Waterharmonica; the biodiversity in the spawning pond at the end of the Waterharmonica at Grou is striking, even at a medium-high load of 0.1-0.2 m/day. We can also reverse the terms of reference and ask ourselves 'how much nature can we feed with water from a Waterharmonica?' and then loads of <0.1 m/day, or even much lower are needed. With a load of 5-10 mm/day (0.005-0.01 m/day), an area can also be kept as a pond or marsh in the summer, too (specific surface area 12.5-25 m^2/p.e.).

- **WATER BUFFERING**

  A Waterharmonica can store water at any load; it is amazing that most are not optimised for water storage because the retention time can then be maintained even with rainwater discharge (under wet conditions). The dimensions of the storage area are then primarily determined by the requisite buffer capacity and the expected degree of contamination, but also by the layout and the natural values. This means that if the main purpose of a Waterharmonica is to store water, a layer of 1.5 m or more can be stored. If higher natural values are aimed for, the rise in the water surface should not exceed 0.5 m. It should be noted that areas with reeds should not be flooded after mowing, as they die off if the stems fill up with water.

So far it seems that a load of approx. 0.25 m/day (= 0.5 m^2 per p.e.) is suitable, certainly in summer, to achieve a good degree of disinfection and catch sludge discharges under wet conditions (e.g. Everstekoog and Grou). In fact, the higher loads, such as those applied at Hapert, in the start-up phase at Land van Cuijk Waterharmonica and at the ecologising filter at Ootmarsum, are too high. They do, however, bring about the first 'ecologising step'. For the design of an 'attractive Waterharmonica aimed at nature and water buffering', it is better to opt for a lower load and a hydraulic load of 0.05 m^3/m^2/day (= 0.05 m/d = approx. 2.5 m^2 per p.e.) can be used as a rule of thumb. This is summarised in table 6.

TABLE 6 **ROUGH GUIDELINES FOR DESIGNING WATERHARMONICAS, SPLIT UP INTO THE LOAD CLASSES 'EXTREMELY LOW' TO 'EXTREMELY HIGH' WITH RELATED SPECIFIC SURFACE AREA REQUIRED EXPRESSED IN NET M2/P.E. (AT 125-150 L/P.E. DAY)**

Load	Net load (m/day)	Net specific surface area (m2/p.e.)	Waterharmonicas per load class as example, see also table 1
Extremely low	< 0.05	> 2.5	Klaterwater
Low	0.05- 0.1	1.25 – 2.5	Elburg
Medium	0.1 – 0.20	0.75 – 1.25	Waterpark Groote Beerze Hapert, Aqualân Grou, the Kristalbad, Ootmarsum, Sint Oedenrode, Soerendonk, Vollenhove
High	0.2 – 0.3	0.5 – 0.75	Everstekoog, Sint Maartensdijk, Land van Cuijk
Extremely high	> 0.3	< 0.5	Tilburg-Noord

To give an idea of the space needed to lay out a Waterharmonica: a surface area of 5 to 25 hectares is needed for a Waterharmonica to treat the entire output of an STP of 100,000 p.e. depending on the functions chosen. Calculations have been made with net loads, needed for the above mentioned functions. For more insights in the effects of specific loads is referred to the full scale experiments carried out in Everstekoog (Schreijer, Kampf et al, 2000). In practice the total, gross, required area will be 1.5 to 2 times more than the net specific area because of banks, access and maintenance roads, natural and recreational layout, etc. see table 2.

If the emphasis is only on disinfection, the retention time is the most significant design parameter, with a logarithmic removal of 0.65 times the retention time. This means that a retention time of three days is required to remove 98-99 %. In ponds with a depth of 1 m, this leads to a net specific surface area of < 0.5 m^2/p.e..

For nutrient removal, the surface load (in kg/ha/year) appears to be the driving factor. The greater the load, the more nutrients are removed in the absolute sense, but the removal efficiency decreases at the same time. The effectiveness can, however, be increased considerably by seeing the nutrients as nutrients in the food chain approach in a nursery system: nutrients can be (temporarily) stored in algae (Uijterlinde and et al, 2011), phototrophic biofilms (Rijstenbil, 2006), aquatic plants, duckweed, etc.

The Waterharmonica is still being developed. The construction of recent versions, such as the Kristalbad, Soerendonk, Sint-Oedenrode and Vollenhove will, if sufficiently monitored, yield a great deal of information in the coming years. The feasibility study of the possibilities for Wetterskip Friesland (Kampf and Boomen, 2013) examined the 28 STPs in Friesland to see which would benefit from the construction of a Waterharmonica. The analysis was carried out for the short and medium term (2012 – 2027). It looked at:

- is enough space available at and around the STP?
- meeting the existing discharge requirements: can a Waterharmonica prevent the possible exceedance of N and P standards and/or suspended solids?
- requirements based on the WFD objectives, both water quality and layout, part of the ecological corridor;
- bathing water, both for ‘official bathing water according to WFD regulations’ and water where ‘people swim’;
- storage and buffering of water;
- nature objectives;
- recreational use;
- reuse; based on the reuse as city, nature, agricultural or industrial water;

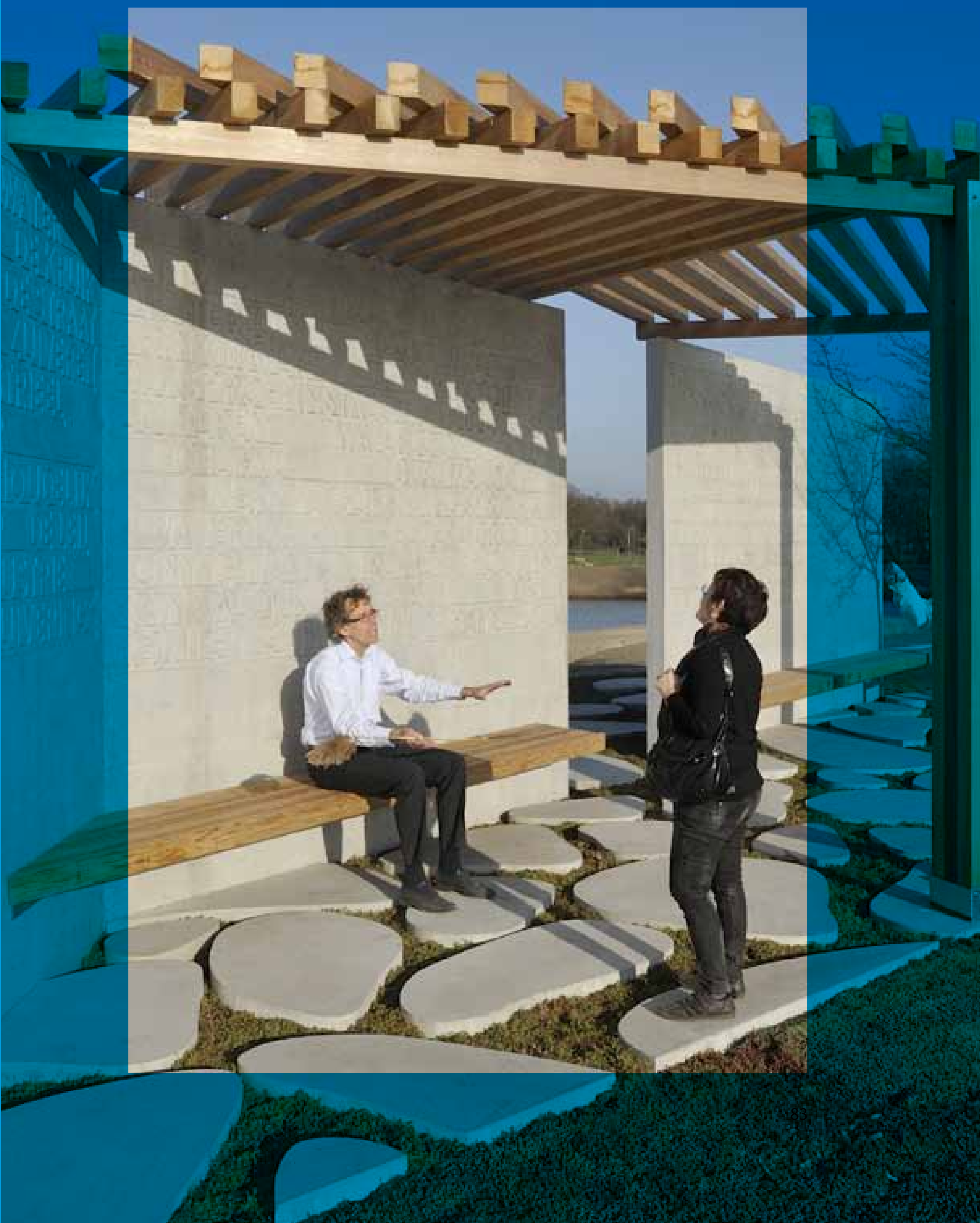
- government levy for the discharge of effluent;
- discharges preventing ice to form on the route of the Elfstedentocht, the famous Frisian 11-city 200 km skating race (or other skating routes).

The results of the quick scan are summarized in table 7. The first column indicates enough or a lack of space on the STP, on most STP's there will be no space on the premises of the STP, and is a search in the neighbourhood needed. For most of the STP's there could be space for a Waterharmonica available. Next columns describe the rating for different aspects. Green + and green ++ are a reason for a local Waterharmonica, a zero means that that aspect is said to be no reason to plan a Waterharmonica for that STP.

Wetterskip Fryslân concluded, based on this quickscan, in the policy plan "Integraal Zuiveringsplan" {Integrated plans sewage treatment} (Fryslân, 2013) that indeed from the point of view of improving the effluent quality a Waterharmonicas is an appropriate solution. But moreover the value is basically a combination of WFD tasks, water system improvement efforts, nature, recreation and desiccation combat. It is a good means to tackle integral water issues with a low-tech, low-energy and cost-effective approach (Sala, Serra et al, 2004). But it also means that in Friesland (and elsewhere!) Waterharmonicas are only possible in a joint effort from many different stakeholders, like the province Fryslân, communities, nature organisations as Staatsbosbeheer, Natuurmonumenten, Fryske Gea and Rijkswaterstaat, the drinking water company Vitens, farmers and residents.

TABLE 7 **PRIORITISATION OF POSSIBLE WATERHARMONICAS IN FRIESLAND**

nr STP	rwzi	sufficient space at STP	sufficient space in vicinity	decrease of discharge to discharge standard	contributes to achieving WFD objective	reduces risks bathing water	enhances nature	fish spawning place/sticklebacks	water storage/WFD layout	recreational values	reuse	preventing ice on skating routes
		Space		Opportunity or significance of a Waterharmonica								
1	Akkrum	+	++	0	0	+	+	+	+	++	0	0
2	Ameland	0	++	0	0	0	++	++	++	++	++	0
3	St.Annaparochie	ponds	+	+	+	0	+	+	+	0	0	0
4	Birdaard	ponds	+	0	0	+	+	+	+	++	0	+
5	Bolsward	-	+	0	0	+	+	+	0	++	0	0
6	Burgum	-	++	++	0	+	+	+	++	+	+	+
7	Damwoude	-	+	++	0	0	+	++		++	0	0
8	Dokkum	-	+	0	+	+	+	+		++	0	0
9	Drachten	-	+	+	+	+	+	+	0	++	0	0
10	Franeker	ponds	+	++	0	0	+	++		+	0	0
11	Gorredijk	ponds	+ / ++	++	+	0	++	0	++	++	++	0
12	Grou	ponds	++	0	0	+	++	++	+	++	0	0
13	Harlingen	-	++	0	0	0	+	0	0	+	0	0
15	Heerenveen	-	++	0	0	+	0 / ++	0 / ++	0 / ++	+	0	0
16	Joure	ponds	+	0	0	+	+	++	++	++	0	0
17	Kootstertille	-	++	0	0	+	++	++	++	++	++	0
18	Leeuwarden	-	0 / ++	0	0	++	++	0	++	++	+	0
19	Lemmer	ponds	++	++	0	+	++		++	++	+	0
20	Oosterwolde	- -	+	+	+	+	+	0	++	++	0	0
21	Schiermonnikoog	ponds	++	0	0	0	++	++	++	++	++	0
22	Sloten	-	++	0	0	++	+	++	++	++	0	+
23	Sneek	-	+	0	+	+	+	+	++	++	0	+
24	Terschelling	ponds	++	0	0	0	++	++	++	++	++	0
25	Vlieland	-	++	0	0	0	++	++	++	++	++	0
26	Warns	+	++	+	0	+	+	+		+	0	+
27	Wolvega	-	++	0	0	+	+	+		+	0	0
28	Workum	ponds	++	0	+	+	+			+	0	+
29	Wijnjewoude	+	+	+	+	+	+		++	+	0	0



11

SIGNIFICANCE OF THE WATERHARMONICA?

The Waterharmonica has now become a concept, a way of thinking, like the terms 'the Water Chain' and 'the Water System'. It is a well-known phenomenon: 'the natural link between the Water Chain and the Water System'. People are also aware of what it is not, such as a sand filter, or a membrane filter for effluent filtration. It is, of course, possible to combine technology and nature, examples being the effluent filtration preceding the Waterharmonicas at Ootmarsum, Kaatsheuvel/Klaterwater, Land van Cuijk and Soerendonk. It is still not clear when this prior filtration is necessary, possibly only for STPs with relatively high loads. In Ootmarsum, under dry weather discharge, all the effluent is filtered (either in the membrane bioreactor or in the sand filter). Under rainwater discharge conditions in Ootmarsum the excess water is led directly to the Waterharmonica after only aerobic treatment. In Empuriabrava, the decision was made not to reuse the effluent via the Waterharmonica when the STP is not functioning well, but to discharge it into the river. An NH_4 analyser was installed for this purpose.

Experience with Waterharmonicas illustrate that much is now known about how useful Waterharmonicas are. Rules of thumb are available for designing them; choices can be made in terms of the performance required, such as the buffering of water and disinfection. It is known that, at lower loads, the systems are effective at capturing and converting nutrients, but also in enlarging the biodiversity, so that the natural values increase. This can easily be linked to recreation and perception. It might also be the case that their greatest value lies in the cooperation of people from totally different backgrounds and interests in an attractive part of the water cycle: an STP manager now sees why he treats the water – and it is not only to meet the standards. The Waterharmonica has proven to be an extremely interdisciplinary and suitable platform for gathering all sorts of disciplines together in an interesting aspect of water management: the natural link between the Water Chain and water management. It is fascinating to quote a conclusion from the WFD study into natural systems for purifying drain and ditch water from agricultural land (Haan, Sival et al, 2011): 'More large-scale opportunities are arising for combinations with other functions such as water storage, nature, recreation and biomass production (for example, Doorn, 1998 and Björk and Graneli, 1978). At sites where the Waterharmonica is combined with an ecological connecting corridor, it can function as a stepping stone or habitat (e.g. the Kristalbad). The Waterharmonica is very well suited to play a role in urban water management, see for plans in several cities, like Apeldoorn, Arnhem and Amstelveen (Veluwe, 2005, Arcadis, 2004 and Leloup, Voort et al, 2012).

A consequence of the Waterharmonica approach is the creation and restoration of wetlands and the conversion of costs of water purification into economic and natural revenues for citizens, but also for water authority. This applies to an even greater extent to the 'developing world' (Mels, Martijn et al, 2005). The sensible use of water and nutrients helps fight poverty and simultaneously conserves and enhances important ecosystems. It is not only the solution to a waste water problem; it is especially an area and ecosystem-oriented approach.

In fact, the short description in the list of definitions in the Water management plan *'2010-2015 Krachtig water* {Powerful water}' drawn up by Waterschap De Dommel is clear: 'Waterharmonica: wetland system which, by biological means, "*brings to life*" the effluent from a sewage treatment plant and, in so doing, minimises the negative effects on the receiving surface water' (De Dommel, 2010a).

The importance of the Waterharmonica was further illustrated at the STOWA symposium *'Post-treatment of STP effluent? Yes, naturally! Practical experiences with the Waterharmonica'.* (29 March 2012) held on the occasion of over fifteen years of practical experience with Waterharmonicas. This day attracted a great many visitors and was extremely lively. For links to the individual presentations, please see (Boomen, Foekema et al, 2012). STOWA produced a film with impressions of the day (Stowa, 2012). More information is available on www.waterharmonica.nl.

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