Phosphorus Project: Sea Breeze IV

Case Denmark

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Sustainable Coastal Management

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Contents

1. Introduction

Eutrophication is a major problem for many coastal areas in the Baltic Sea region, with the underlying cause being nutrient pollution. Phosphorus constitutes a major part of that nutrient pollution. In addition to its detrimental effects on the environment, phosphorus is also a critical resource: it is needed in our food production thus it is essential for life. It is also non-substitutable, non-renewable and there is an increasing demand for phosphorus because of the population growth and pressure to produce more biofuels. All this makes the proper usage, reuse and recycling methods of phosphorus even more important.

In this report, the status and management of phosphorus pollution in Denmark will be described. First, an overview of phosphorus pollution is given in chapter 2. The following chapters present phosphorus regulations and treatment in different fields: agriculture (chapter 3), sewage treatment (chapter 4) and aquaculture (chapter 5). Chapter 6 presents best practices in Danish phosphorus management. Finally, conclusions are drawn in chapter 7.

2. Phosphorus pollution in Denmark

Denmark is among the three largest sources of phosphorus discharges into the Baltic Sea (HELCOM 2011, 37). Its waterborne phosphorus load to the Baltic Sea is 1520 tonnes (5,4% of total phosphorus load) which originates mostly from unmonitored areas (HELCOM 2011, 31-33).

The biggest point source of phosphorus is the municipal waste water treatment plants (figure 1) (HELCOM 2011, 37). In terms of phosphorus demand in Denmark, the annual phosphorus demand in agriculture is 53 000 tonnes per year. While the phosphorus import is between 15 000 and 20 000 tonnes annually, there is a major potential for phosphorus recycling. For waste water treatment plants the recycling potential is 5000 tonnes, for manure 45 000 tonnes, and for households, service and industries 9000 tonnes annually. (Thomsen, 2013)

Because of the major demand and the great recycling potential of agriculture, it has possibly the greatest impact on the Danish phosphorus pollution. According to the vision of the Danish government, the organic farm area must be doubled in 2020. Currently the organic farming area is being converted with the rate of 7000-8000 hectares per year. In order to match the government's vision, the conversion should be as much as 18000 hectares per year. However, since the organic fertilizers for organic farming are scarce, recycling of phosphorus is needed: sludge, municipal and industrial waste could be transformed into phosphorus fertilizer. (Thomsen 2013)

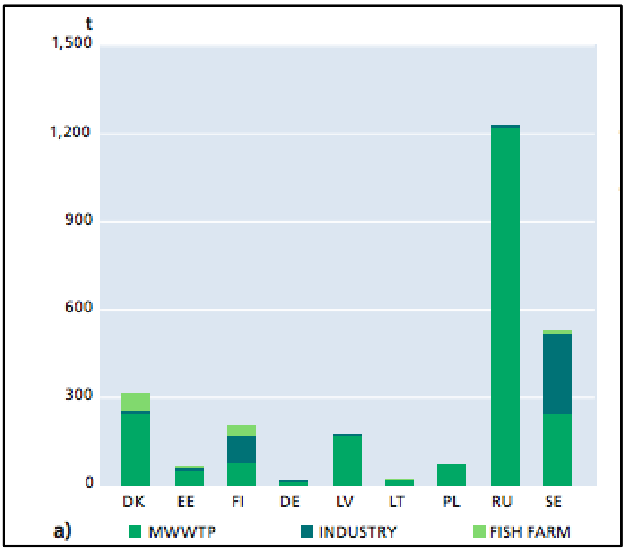

Figure 1. Direct point source phosphorus load in tonnes into the Baltic Sea by country. DK=Denmark, MWWTP = municipal waste water treatment plants (HELCOM 2011, 37)

3. Agriculture: phosphorus regulations and treatment

3.1 State of agriculture in Denmark and main cultivated species

Over 66% of Denmark's total land area is used for agriculture (Statistics Denmark, 2014a). Agriculture in Denmark is the oldest and one of the largest factors of Danish national economy. About two thirds of the Danish agricultural production is exported all over the world (Facts about Danish Agriculture, 2014). About half of the export goes to EU-countries.

The main crops in Denmark are cereals, which cover more than half of the agricultural area (Statistics Denmark, 2014b). Danish farmers produce 22 million slaughter hogs per year. Besides large quantities of pork and dairy products, Denmark produces beef, poultry and fur skins for the Danish market and for export (Facts about Danish Agriculture, 2014).

3.2 Agriculture as a source of phosphorus loading

Generally the sources of phosphorus loading can be divided into point sources and diffuse sources. Due to the amount of phosphorus from point sources has declined, the contribution proportion from diffuse sources, mostly from agriculture, has relatively increased nowadays.

The phosphorus losses into Baltic Sea from diffuse sources for countries demonstrated that agricultural activities played a major role (figure 2). And the proportion of total phosphorus loading from agriculture in Denmark is approximately 57% in 2006.

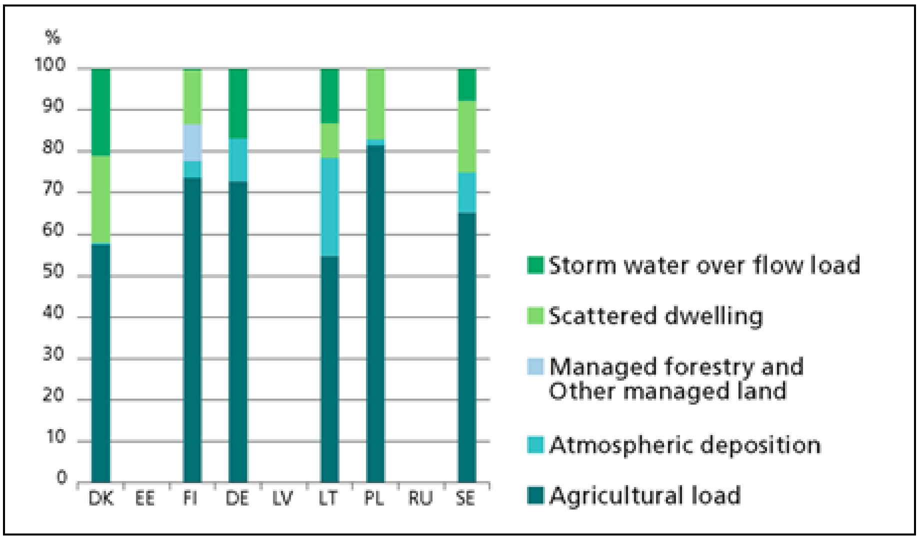

Figure 2. Anthropogenic diffuse total P load into the Baltic Sea by source (in %) and by country in 2006. DK=Denmark (HELCOM 2011, 43)

Because phosphorus is required in relatively large amounts for plants growth, it is an essential element classified as a macronutrient. Appropriate P availability for plants stimulates early plant growth and accelerates maturity. Despite the fact that P is needed for plant growth, poor P management in soil may pose a risk to water quality. In freshwaters the concentration of P is usually low enough to inhibit algal growth. In case of P polluted lakes and rivers, excessive growth of algae is observed (Schierer et al. 2007). A generalised P-cycle for agricultural soils at farm level is illustrated in figure 3.

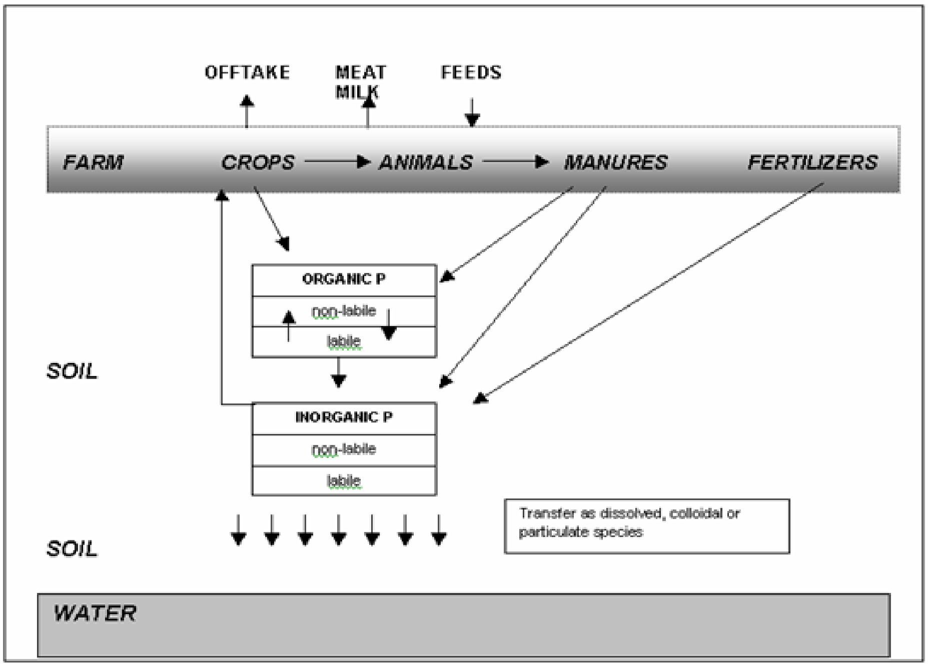

Figure 3: Generalised P-cycle at farm level (Bomans et al. 2005)

There are three categories of P losses from agricultural lands: a) flash losses of soluble forms of phosphorus shortly after manure or fertilizer application, b) losses of soluble phosphorus as a result of slow leaking or c) erosion processes (Wiederholt & Johnson, 2005).

Agriculture is a considerable source of phosphorus inputs to the Baltic Sea. Diffuse loading makes reducing phosphorus loads from agriculture more complicated than simply cutting loads from point sources (HELCOM 2011, 85). To reduce the phosphorus input from agriculture to the sea, there are some major measure may help: changes in the number of livestock, leading to a reduction in manure application, and reductions in the usage of mineral fertilizers.

3.3 Legal regulations related to agriculture and phosphorus

The Danish third Action Plans for the Aquatic Environment (APAE III) includes a stronger focus on surplus phosphorus in agriculture, which is the first action plan to regulate P handling in agriculture. The objectives of APAE III are to further reduce excess phosphorus from agriculture by 50% by 2015, compared to 37,700 tonnes P in 2001/2002 (Danish Environmental Protection Agency).

Phosphorus from manure is indirectly restricted due to the limit of 140-170 kg N/ha/y for the entire Danish territory. There are guidelines for the optimum phosphorus amount for the most important agricultural crops, and tables with P-amounts in manure are available (Bomans et al. 2005). Maximum application rates for total phosphorus are in effect only on a consultative basis (Anon., 2013a). However, until now there are no controls and no penalties on the amount of P in manure and the P given to crops.

A tax of DKK 4 per kg of mineral phosphates for feed (Anon., 2004) was introduced in 2005, the only such case in the EU, which has generally resulted in reduced phosphorus excretion (Damgaard 2005; Damgaard 2013). Phosphorus application by organic fertilizers consisting of less than 75% manure (mainly sludge) is restricted to 30 kg P/ha/y over a period of 3 years and to a maximum of 7 tonnes dry matter/ha/y (Anon., 2006).

There are additional restrictions for the manure phosphorus surplus for animal farms that meet all three of the following criteria: 1) farms that want to expand or change their production unit, 2) farms that drain into Nature 2000 areas overloaded with P and 3) farms that fall under P class 1, 2 or 3 (table 1) (Anon., 2013b). When the manure account is in balance, no further restrictions are applied. If the surplus is positive, restrictions are applied, depending upon the soil type and phosphorus status:

Class	Soil type	Additional restrictions
Class 0	drained clay soils, Olsen-P < 4	no additional restrictions
Class 1	drained clay soils, 4 < Olsen-P < 6	phosphorus surplus can increase at maximum by 4 kg P/ha/y
Class 2	lowlands with Fe/P mole ratio < 20	phosphorus surplus is at maximum 2 kg P/ha/y
Class 3	drained clay soils, Olsen-P > 6	No phosphorus surplus is allowed

Table 1. Phosphorus classes (Amery & Schoumans, 2014)

3.4 Phosphorus index

Phosphorus index (P-index) is a tool that helps estimate the risk of phosphorus losses from agricultural fields. In the P-index, best available site-specific knowledge about the different processes affecting phosphorus losses is combined to produce a risk estimate. (Baltic Deal, 2011)

In Denmark, the P-index has been developed by researchers and tested in practice in cooperation with the farm advisory service. Farmers and their advisers are apparently satisfied with the tool, while the authorities hesitate, probably because they fear the costs of the enforcement. (Baltic Sea 2020, 2011)

The index tool is web-based, consisting of pre-calculated P-index maps covering the entire Denmark as well as phosphorus mitigation planning tools. The Danish P-index is more complicated in its structure than for instance the Norwegian one. The major challenges are lack of data (mainly on soil P status), and uncertainties or need for additional validation of the model. Furthermore, it requires some practice by the user to interpret. Nowadays, the tool is not maintained due to lack of funding. (Baltic Sea 2020, 2011)

4. Phosphorus in sewage treatment: regulations and practices

The municipal wastewater treatment plants are the biggest point source of phosphorus pollution (HELCOM 2011, 37). Wastewater is typically discharged into rivers, lakes or sea or filtered into the ground. The discharges affect surface waters by causing anoxic (i.e. oxygen-depleted) conditions and increasing eutrophication. However, in Denmark there has been a significant reduction in the total outlet of wastewater nutrient pollution since the mid-1980s. Phosphorus pollution reduction is about 85% due to better wastewater treatment and decreasing industrial discharges. (Baaner & Anker 2013, 40)

4.1 Wastewater treatment capacity and regulations

Danish wastewater treatment plants (WWTP) treat approximately 630 million m3 of waste water annually both from household and industry sources. (Biocorrection w.y.) There are about 1100 WWTPs that are treating water up to tertiary treatment for communities of 30 people or more. The national wastewater production volume has an increasing trend but the number of WWTPs is decreasing due to the enlarged capacity and centralized treatment. (Arias w.y.) The water and sanitation sector is decentralized: it is run by utility companies that are owned and managed by the municipalities and consumer-owned corporations (Baaner & Anker 2013, 41).

The treatment of waste water produces about 1.2 million tons of wet sludge, corresponding to about 160 000 tons of dry sludge annually. The content of the dry sludge reused as fertilizer in agriculture varies in municipalities. It is estimated that half of the sludge is used by the farming industry and the other half is incinerated, dumped or used for other purposes. (Biocorrection w.y.)

Aspect	**Denmark**	**The EU**
Treatment techniques (agricultural use)	Stabilisation, composting, pasteurisation	Biological, chemical, heat, long term storage, or other process significantly reducing health hazards
Use of untreated sludge (agricultural use)	Forbidden	Member States are allowed to lay down conditions of the use of unthreaded sludge (if it is injected or worked into the soil)
Pathogen limit values (agricultural use)	No occurrence of *Salmonella*, fecal streptococci <100/g	--
Organic compounds limit values (agricultural use)	DEHP, PHAs, NPE, LAS	--
Max. quantities applied to the soil (agricultural use)	7 tonnes of dry matter / ha / year	Member states shall lay down max. quantities of sludge which may be applied to the soil
Frequency of analysis (agricultural use)	Sludge: for heavy metals - every 3 months, org. compounds - annually; Soil: before 1st application	Sludge: 1-2/year. Soil: before first application (Member State may decide on further frequency)
Use in forestry, silviculture, land reclamation, green areas	In forestry - if local councils allow; in green areas - pasteurised	Not regulated by Sewage Sludge Directive (86/278/EEC)
Incineration / landfilling	--	Landfill Directive (1999/31/EC). Incineration Directive (2000/76/EC)

Table 2. The comparison between Danish sludge handling and EU regulation (PURE 2014)

Wastewater treatment in Denmark has been improved over the years through government and EU regulations. As a member of the EU, Denmark implemented the requirements set in 1994 which resulted in upgrading or constructing new systems for all the municipalities with populations above 5000. (Arias w.y.) The framework for wastewater regulation includes the Environmental Protection Act, the Act on Wastewater Payment, the Act on Taxes on Wastewater and the Act on the Water Companies (Baaner & Anker 2013, 44). The comparison between the EU and Danish legislation (table 2) shows that there are differences in how different aspects of waste water treatment are regulated (PURE 2014).

4.2 Household sewage management

In the Baltic Sea Region, municipalities are the major source of nutrients (90%) (HELCOM 2014). In Denmark, water supply and sanitation are considered a responsibility of the local government. Private household can choose from being connected to the public sewage system or have their individual sewage treatment system. In general, urban areas are connected to the public system whereas in rural areas private systems are more common. (Baaner & Anker 2013, 47).

There are in total 820 municipal wastewater treatment plants in Denmark with total load of 6 960 000. Most of them are of the smallest size category, for less or equal to 2000 population equivalent (PE) (figure 4). (HELCOM 2011, 19)

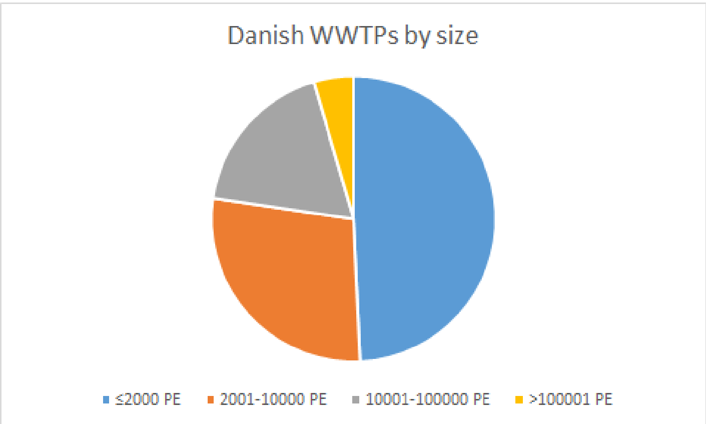

Figure 4. Municipal wastewater treatment plants by size (HELCOM 2011, 19)

Denmark has a very high level of municipality waste water treatment. In 2009, 90% of the Danish households were connected to urban wastewater collection. This is the second highest level after Germany. Also the portion of tertiary treatment systems is high compared to other Baltic Sea countries: 88% of households have tertiary treatment, secondary treatment is in 90% of households and only 0.4% of households have primary treatment. (HELCOM 2011, 19)

4.2.1 Removal requirements and capacities of sewage treatment systems

In rural areas, a zoning procedure is used in order to classify different areas and assign permissions and injunctions. The classes formed through zoning set the requirements for the capacity of the wastewater treatment system to phosphorus, nitrogen and organic matter. The classes and their requirements (table 3) are in line with the HELCOM recommendation. (Baaner & Anker 2013, 48-49)

Type	**Organic matter**	**Total P**	**Nitrification**
SOP	95%	90%	90%
SO	95%		90%
OP	90%	90%	
O	90%		

Table 3. Treatment class and removal requirements according to the Danish Environmental Protection Agency SOP=removal of organic material, phosphorus and ammonia, SO= removal of organic material and ammonia, OP= removal of organic material and phosphorus, O= removal of organic material (Arias w.y.)

Solutions that meet the requirements above are small wastewater treatment plants, willow-based evaporative systems and percolation of wastewater after filtering process. The Danish Environmental Protection Agency (EPA), an agency responsible for environmental policy, has guidelines for these. (Baaner & Anker 2013, 49) In table 4, the removal capacity of different waste water treatment systems is presented.

Class	**Infiltration**	**Willow systems**	**Constructed wetland (SF)**	**Constructed wetland (VF)**	**Biological sand filter**	**Technical systems**
SOP	X	X		(X)*	(X)*	X
SO	X	X		X	X	X
OP	X	X		(X)*	(X)*	X
O	X	X	X	X	X	X

Table 4. System’s removal class and removal capacity. SOP=removal of organic material, phosphorus and ammonia, SO= removal of organic material and ammonia, OP= removal of organic material and phosphorus, O= removal of organic material (Arias w.y.)

According to the EPA's guidelines, issues may arise if wastewater from properties in rural areas is discharged into the aquatic environment after being treated in a small-scale biological treatment system, or if the wastewater is percolated untreated into the ground after a simple settlement of solids (primary treatment). However, the municipality can order improved treatment of wastewater in rural areas only if the drainage system and point of discharge is known and if the discharge enhances pollution in an aquatic environment where the environmental objectives are not met. (Baaner & Anker 2013, 49)

In the following chapter, one of the small-scale wastewater treatment methods is presented.

4.2.2 Constructed wetland systems

Constructed wetland systems for wastewater treatment have been in operation in Denmark since early 1980s. There are about 170 constructed wetland systems and 100 willow-based evaporative systems for the household sewage treatment. In addition, there are roughly 50 restored wetland projects for nitrate removal from surface and drain water. (Brix et al. 2007, 63-64)

The majority of the constructed wetland systems and willow-based evaporative systems are meant for treating domestic sewage from small villages in rural areas. They can also be used to treat wastewater from schools, camping sites, run-off from roads and effluent from some food-processing factories as well as on-site systems for single households and farms. Often in rural areas the sewerage systems are combined thus the reed beds are used for both rainwater and sewage treatment. (Brix et al. 2007, 64-65)

At the time of launching, the constructed wetland systems were considered a low-cost and high-performance wastewater treatment method. With growing usage experience, it was acknowledged that the performance was not as good as expected, thus new designs based on gravel and vertical flow were developed and various means of sustained phosphorus removal were tested. (Brix et al. 2007, 63) The modern Danish designs are compact vertical flow systems that have considerably higher capacity and provide a nitrified effluent, willow systems with no outflow and restored wetland for removal of nitrate from surface waters. (Brix et al. 2007, 68)

In general, the constructed wetland systems are easy to operate. They can be built in any area and they are simple to construct and maintain. The removal of nitrogen and phosphorus is roughly 30-50% and the phosphorus treatment performance seems to remain stable over time as the systems mature (Brix et al. 2007, 67-68) Also, there is little seasonal variation in treatment performance although the water temperature varies by more than 10 Celsius degrees. (Brix 1998 according to Brix et al. 2007, 67).

Constructed wetlands can also be used for wastewater sludge treatment. The sludge treatment reed bed (STRB) technology has been successfully used and improved especially in Denmark and France and it is suitable for all kinds of sludge: primary, secondary and post-fermentation sludge or sludge from septic tanks. (Kolecka & Obarska-Pempkowiak 2013, 1412) The long-term stabilization of sewage sludge in STRBs causes an increase of phosphorus concentration. In addition to the high concentrations of phosphorus, the stabilized sludge contains nitrogen compounds and only low concentrations of heavy metals, which makes the stabilized sludge a great fertilizer. (Kolecka & Obarska-Pempkowiak 2013, 1415-1417)

4.3 Industrial sewage management

Industrial sources remain as one of the major sources of contamination of the Baltic Sea. Usually contamination occurs through discharges into water bodies. In the Baltic Sea region, point sources (both industrial and municipal discharges) contribute for total waterborne load by 20% of phosphorus, corresponding to 6000 tons of phosphorus. In Denmark, phosphorus discharges from industry were reduced by approximately 85% between the end of 1980s and 1995 and the decrease continued by 31% between 1994 and 2008. Further reductions in point source phosphorus discharges are becoming increasingly difficult to achieve. (HELCOM 2014, HELCOM 2011)

According to HELCOM regulations that are applied in Denmark, water management in industrial plants should aim at closed water systems or at a high rate of circulation. Also, industrial wastewaters should be separately treated before mixing with diluting waters and the improvement of waste water quality should not lead to a significant increase in the amount of detrimental sludge. (HELCOM 2014). However, with the existing sewage systems, the separation of household waste water from industry waste water is not possible. Thus many of the larger industrial plants have on-site water treatment plants. (Biocorrection w.y.)

One solution to the industrial waste water treatment is anaerobic digestion plant. By using anaerobic digestion technology, different sources can be combined and as result dewatered sludge and biogas are produced. Denmark, this technology has been adopted with success. In chapter 6.1, the anaerobic digestion technology and its utilization in renewable energy production is described in more detail.

5. Aquaculture and phosphorus

From here onwards we will define aquaculture as "*farming of freshwater and saltwater organisms including fish, molluscs and crustaceans*" (Food and Agriculture Organization of the United Nations, 1997).

5.1 State of aquaculture in Denmark and main cultivated species

Aquaculture in Denmark has a strong position. About 20 000 people in Denmark are employed in fishing, aquaculture and associated sectors (Ministry of Food, Agriculture and Fisheries of Denmark, 2014), with 5% share of aquaculture in the above stated sectors (figure 5).

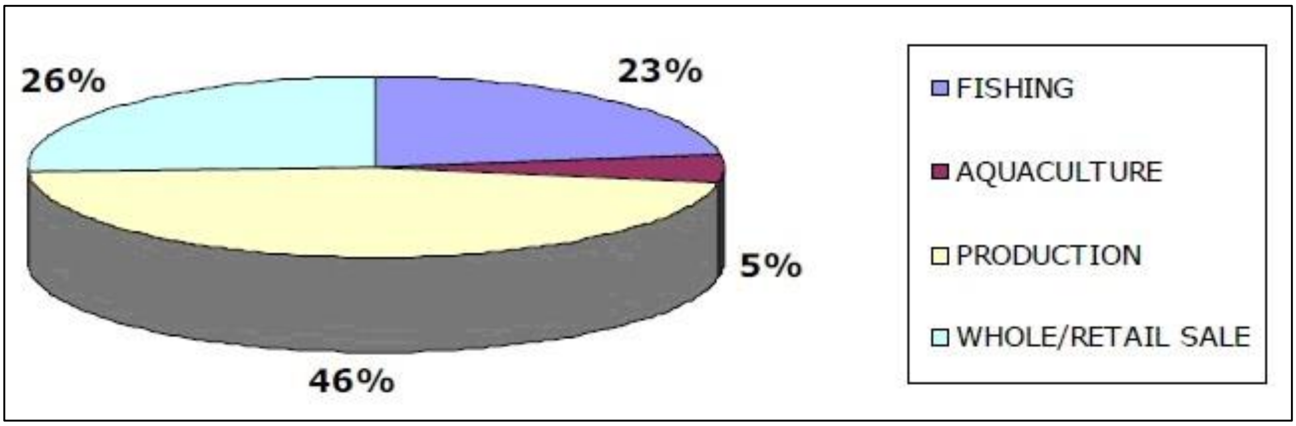

Figure 5. Employment in fisheries and aquaculture in Denmark in 2009 (Semrau, Ortega Gras and Policy Department B, 2013)

This 5% share of aquaculture can be considered a rather high rate: in 2011 Denmark was the 9th in EU according to its total volume of aquaculture production (European Commission, 2014, 26) with a high demand. In 2003 over 90% of Denmark's aquaculture products were exported (Food and Agriculture Organization of the United Nations, 2015). Table 5 contains statistics on species produced through Danish aquaculture shown their net weight. The main cultivated species are rainbow trout, European eel and blue mussels with rainbow trout being the dominant cultured species with 93% share in the net weight of all cultivated species (figure 6).

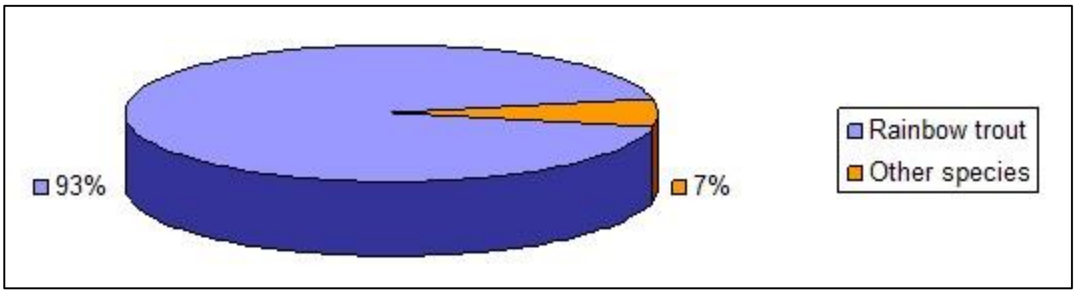

Figure 6. Share of rainbow trout in net weight of aquaculture species in Denmark.

Species	Production (weight, tonnes)
Rainbow trout	33989
European eel	1079
Blue mussel	560
Char	272
Sea belt	180
Pike-perch	112
Sea trout	78
Brook trout	76
Brown trout	52
Atlantic salmon	22
Turbot	7
European perch	3
Northern pike	2
Sturgeon	2
Pollan	0*
Common carp	0*
European flounder	0*
Total weight	36432

* Nulls in the table stand for less than 0,5 tonnes.

Table 5. Net production of aquaculture species in Denmark in 2013 based on data by Danish AgriFish Agency (Danish AgriFish Agency, 2014 b)

All Danish aquaculture farms are registered in the Central Husbandry Register of Denmark (Danish Veterinary and Food Administration, 2014). At the moment the online Central Husbandry Register shows 240 aquaculture farms with specialization in salmonid fish to which rainbow trout belongs (CHR, 2015).

5.2 Aquaculture as a source of phosphorus loading

Aimed to satisfy the demand for aquatic foods and being an important production issue in today's economics, aquaculture, however, creates a risk of nutrients discharges (including phosphorus discharges) and can be considered a source of nutrient pollution (EEA, 2010, 38) although the rate of phosphorus loading from aquaculture compared to one from agriculture is low (EPA, 1995) (see table 6).

Source	**Total phosphorus (mg/l)**
Fish farms	0,07
Dairy shed effluent	340
Feedlot effluent	150

Table 6. Nutrients concentrations from fish farms in comparison to agricultural sources (EPA, 1995)

The path of phosphorus losses from aquaculture has been analyzed in details by Kibria, Nugegoda, Lam and Fairclough (1996, 21). The following sources of phosphorus from aquaculture are listed by the authors: uneaten food and food fines, animal excreta (feces and urine), and dead animal tissues (visualized as a flow chart on figure 7). As it can be seen from the chart, phosphorus from aquaculture is received into the environment in two forms: particulate and dissolved phosphorus. Particulate phosphorus may come into the water in an organic or inorganic form. Dissolved phosphorus is present in water as orthophosphate – soluble reactive phosphorus which is inorganic (Carlson & Simpson, 1996).

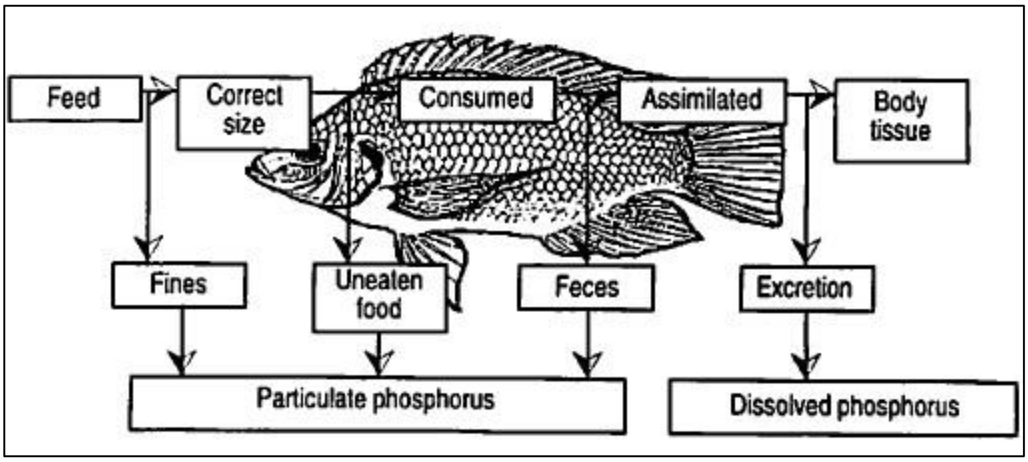

Figure 7. Phosphorus losses path in aquaculture (Kibria, Nugegoda, Lam & Fairclough, 1996)

Nevertheless, the situation with phosphorus loading from aquaculture is controllable, and there are opportunities to reduce phosphorus losses from aquaculture through appropriate management.

Certain amounts of phosphorus losses depend on a type of aquaculture farming (or aquaculture technology) (Jokumsen & Svendsen 2010, 22), temperature (Kibria et al. 1996, 21), farmed species (EEA 2010, 38), a feed method (trash feed type versus dry or moist one) (Kibria et al. 1996), and a diet of the farmed animals (Kibria et al. 1996; Harbell, w.y.; Hardy & Gatlin, 2002). Jokumsen and Svendsen (2010) prove by the example of farming rainbow trout in Denmark that different aquaculture farm types also play a part in different levels of phosphorus loading.

5.3 Legal regulations related to aquaculture and phosphorus in Denmark

The environmental legislation and regulations of freshwater fish farms in Denmark are represented by:

- the Environmental Protection Act (1974),
- the Statutory Order (1985) forbidding wet feed,
- the Action Plan on the Aquatic Environment (1987) implemented through the measures stipulated in the Statutory Order on Fish Farms (1989) (Iversen, 1995).

Since aquaculture absolutely depends on water and impacts on it, the EU Water Framework Directive (WFD) which defines water quality standards is also relevant to these activities. Denmark implements the WFD under the Environmental Target Act, or the Act on Environmental Objectives (2003) (Baaner & Anker, 2013).

The Danish Environmental Protection Agency has assessed the water quality criteria (WQC) for each agent in the receiving waters (streams, rivers, lakes). All fish farms are obliged to meet specific requirements in water treatment and quality of discharging water in accordance to the WQC. These requirements are written down in the environmental approval given for each individual farm (Jokumsen & Svendsen, 2010, 15).

Besides nutrients concentrations in the outlet from farms, many other parameters must be monitored by farmers, including ones connected with nutrients concentrations: the maximum allowable annual feed consumption and the maximum concentration for organic and suspended matter (Jokumsen & Svendsen, 2010, 4).

According to the Statutory Order on Fish Farms (1989), the phosphorus content of the feed must not exceed 1% of the dry weight of the feed (9% are allowed for nitrogen) (Jokumsen & Svendsen, 2010, 13).

Already by the year of 1995 the national goals of the Action Plan on the Aquatic Environment (1987) for reducing fish farm discharges of organic matter, nitrogen and phosphorus have been fulfilled. (Iversen 1995, 73).

5.4 Main trout production technologies in relation to phosphorus reduction

Here we will base our review of Danish aquaculture technologies on the ones which are used in the rainbow trout production. It is the rainbow trout production that can be considered the largest risk of undesirable phosphorus discharges from aquaculture in Denmark because of two reasons:

- Rainbow trout is classified as *Salmonidae*, and salmonid finfish farming forms the largest pressure associated with nutrients discharges from aquaculture (EEA 2010, 38);
- As shown above, rainbow trout is an absolutely predominant aquaculture species in Denmark.

Thus it is logical to assume that the trout production forms the largest threat for phosphorus discharges from aquaculture, and comparison of technologies used in trout farming is the best way to illustrate the effectiveness of Danish aquaculture technologies in reduction of phosphorus losses.

Currently in Denmark there are four main technologies in use for the rainbow trout production which show different efficiency in phosphorus reduction:

- traditional freshwater farms,
- sea farms (offshore farms),
- Danish model farms,
- FREA (fully recirculation aquaculture)-based farms (also known as RAS - recirculating aquaculture systems).

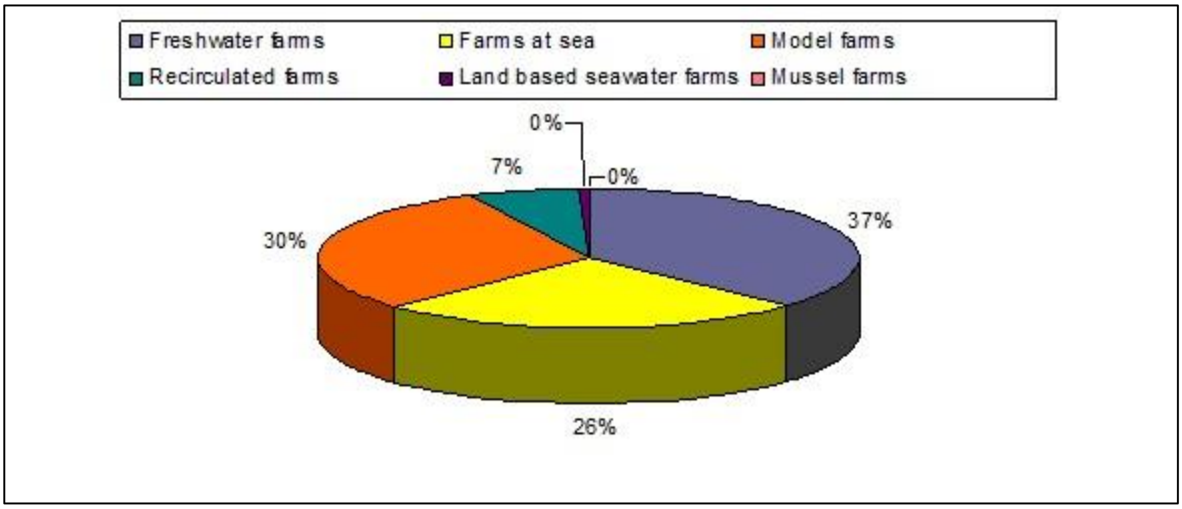

Figure 8. Share of trout production in tonnes in 2013 grouped by technology of production based on the data of the Danish AgriFish (Danish AgriFish Agency, 2014a)

Danish model farms and FREA/RAS farms are the advanced technologies for removing phosphorus and can serve as an illustration of the best Danish environmental practices. Their operational principles and effectiveness in phosphorus reduction are described in chapter 6.2.

However, figure 8 shows that currently more than a half of farmed rainbow trout is produced with use of less sustainable technologies - traditional freshwater and sea farms. Below we will describe problems of using these technologies in relation to effective phosphorus reduction.

5.4.1 Problems of phosphorus discharges from traditional freshwater farms

The idea of a traditional aquaculture farm is to use a freshwater damming (or a bypass) as a habitat for cultivating aquatic animals. Inflow water flows through the dam with farmed fish and passes through it by gravity. Sometimes minimal equipment can be used in traditional farming: grids for preventing the fish escape, pumps for pumping out water, and a tank made of waterproof materials instead of the earthen damming (Jokumsen & Svendsen, 2010, 18). Anyway, the out-flowing water is not treated, and the effluents sweep away farm sediments, fish solid wastes, uneaten food and food fines into lakes and seas.

Since 1989, according to the first edition of the Regulation relative to freshwater fish farms (Bekendtgørelse om ferskvandsdambrug, 1998), unregulated waste discharges from trout farms have been forbidden. Construction of settling basins for a nutrients removal became compulsory, and a requirement of regular chemical sampling of inlets and outlets in order to report on nutrients discharges was established. Without the effective utilization of nutrients, increasing volumes of production was not allowed.

These factors caused converting of many traditional farms into a new improved farm type – model farms in order to optimize water treatment management (Jokumsen & Svendsen, 2010, 5). However, according to statistical data, in 2013 37% of trout in Denmark (15099 tonnes) was still produced at farms using the traditional production technology (marked as freshwater farms in table 7 and in figure 8).

Technology of production	**Production in tonnes**
Freshwater farms	15099
Farms at sea	10505
Model type III	9025
Model type I	3119
Recirculated farms	2823
Land based seawater farms	159
Mussel farms	14

Table 7. Rainbow trout production in tonnes in 2013 grouped by technology of production (Danish AgriFish Agency, 2014a)

5.4.2 Sea farming: disputable impacts on the phosphorus reduction

Sea farming of trout is the second popular technology of trout production in Denmark: in 2013 26% of Danish trout was produced at sea farms (figure 8). Sea farming implies cultivating trout in a comparatively large offshore area where the fish is kept in cages (figure 9).

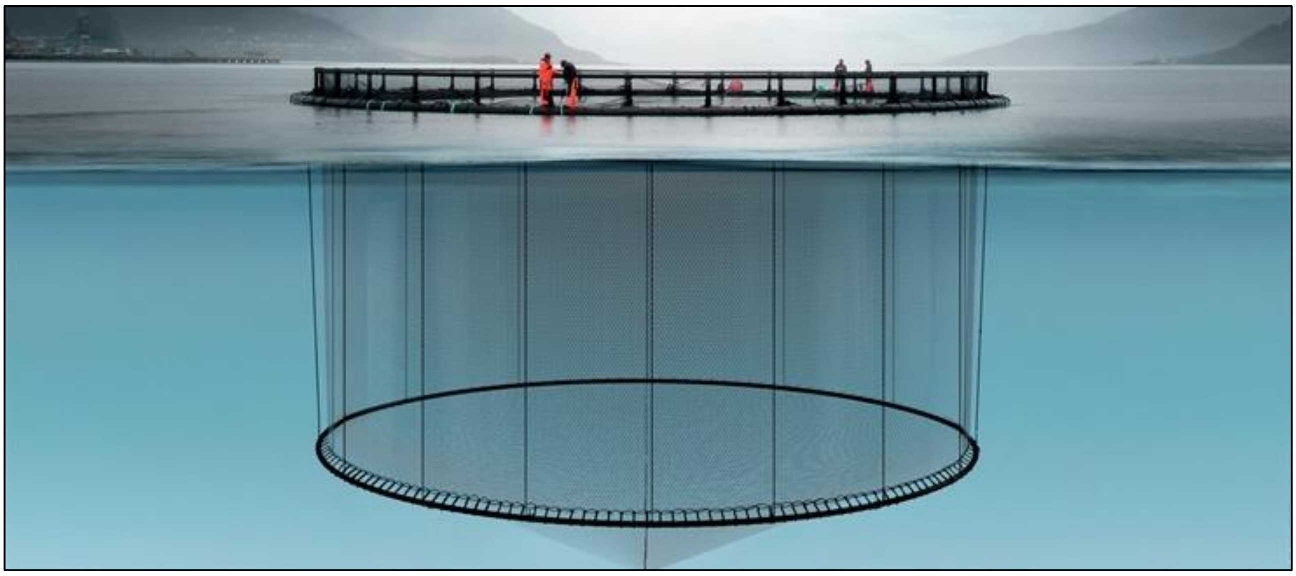

Figure 9. Fish cage for offshore aquaculture (Akva Group, 2012).

On one hand, larger areas and volumes of water let farmers lessen concentrations of nutrients in water. Moreover, sea plants and the other sea organisms may help in phosphorus reduction: plants use some amounts of phosphorus for living, animals eat sediments rich in phosphorus: solid wastes, feed fines and uneaten food. On the other hand, phosphorus at sea farms is not fully removed. The effectiveness of phosphorus and the other nutrients removal in offshore farming varies and depends on areas engaged with the farm, currents, temperature, presence of seaweeds that remove nutrients, seaweed closeness to fish cages (Troell et al. 2009, 5-6), and other factors (a size of populations grown, a diet, etc.). In many cases effectiveness of nutrients removal is hard to predict and it makes impacts of sea farming on phosphorus loading disputable.

Although the described technologies have obvious problems with phosphorus reduction they are still rather popular in today's Denmark. However, Denmark has alternative ways of aquaculture development - currently 37% of farmed rainbow trout (see figure 8) is produced with use of new and advanced aquaculture technologies: model farming (30%) and FREA/RAS systems (7%). The description of these technologies is presented in chapter 6.2.

6. Best practices in phosphorus treatment

In this chapter, success stories of phosphorus treatment in Denmark are presented. The following two cases, biogas production through anaerobic digestion and phosphorus reduction technologies in aquaculture, demonstrate some of the best Danish practices for phosphorus management.

6.1 From waste to energy - biogas production from industrial and household waste

Denmark developed a major program for biogas production from household waste, sewage sludge, industrial wastewater and retail food waste using anaerobic digestion technology. One of the major factors leading to its development was that suitable industrial waste water streams that form the bulk of the waste are sufficiently available on a continuous basis. (Waste Management World 2010)

6.1.1 Anaerobic digestion plant and biogas production

When using anaerobic digestion technology, waste and sludge from different sources are co-digested. In an anaerobic digestion plant, the collected waste is stored and blended after which it is pasteurized and digested at 35°C. The end-products are dewatered sludge, which is spread on land and used as a fertilizer, and biogas, which is used for producing electricity and heating. (Waste Management World 2010)

The anaerobic digestion plant was built in Grindsted municipality in 1996. In 2010, it produced around 2.5 million m3 per year of biogas which is used for generating electricity and providing district heating. The odourless digested sludge is dewatered to 22% dry solids and spread on farming land (in the wintertime, the sludge is stored). With the initial investment of € 8.5 million, the plant has reduced the waste by 60% and degrades the waste by the same amount. The municipality has plans to increase the biogas production volumes to over 26 million m3 per year in the future. (Waste Management World 2010)

6.1.2 Success factors

There are several factors that led to the successful implementation of the biogas program (Waste Management World 2010):

1. **Supporting governmental policies:** The support of the Danish Government via their energy policy was essential. The biogas program is in line with the government's renewable energy plan called "Energi 21" that sets a goal of producing 35% of energy from renewable sources such as biogas.
2. **Availability of technologies:** Krüger A/S, part of Veolia Water Solutions & Technology, has had an important role in developing the anaerobic digestion technology currently used in Denmark. Veolia Group with its subsidiaries and versatile services was able to provide a comprehensive solution to the municipality.

3. **Availability of suitable waste sources:** The availability of suitable industrial waste streams on a continuous basis is essential in a major investment and in an industrial process like this.
4. **Infrastructure:** Before the treatment, viable disposal route for sludge is needed. After the treatment, there needs to be a disposal route for the treated liquid product. Also, for energy distribution there needs to be the necessary infrastructure. Infrastructure plays a major role in waste management and especially in this case.
5. **Synergies:** Biogas production from the waste is a win-win situation. For factories and other industrial companies needing a solution for waste treatment, it is a cost-effective way for waste treatment. For municipality, it is a cost-effective way to produce electricity, reduce waste, minimize phosphorus pollution and recycle nutrients.
6. **Co-operation of the local public:** Anaerobic digestion requires waste source segregation in order to have a digestible feed. In this case, source segregation was possible because good communications motivated the public to sort their waste. The segregation was further encouraged by introducing a fines system for households that refused to sort their waste.

By combining different waste streams and using a technology that allows them to be handled together Grindsted municipality has turned their waste into a resource. In addition to the biogas production that provides heating and electricity, the digested sludge is utilized as fertilizer.

6.2 Recirculation based systems - Danish way to more sustainable aquaculture

Among the most popular aquaculture technologies used in Denmark (see table 7 and figure 8), Danish model farming and FREA/RAS technologies are considered to be the most sustainable. The invention of model farms and then FREA/RAS systems was two sequential steps which helped to improve the situation with phosphorus loading from aquaculture. Both technologies are based on the idea of treatment of outflowing water rich in nutrients and reusing it. Below the prerequisites for establishing, operational principles, efficiency in phosphorus reduction and the current state of these technologies are described.

6.2.1 Danish model farms: improved technologies of phosphorus reduction

Model farming is a Danish invention that made it easier to meet the toughened requirements for water quality, including the requirements for levels of nitrogen (ammonia, nitrate, and total nitrogen) and phosphorus (dissolved and total). Model farms imply mechanical (sometimes accompanied with biological) water treatment and reuse of water via various combinations of the following equipment: sludge cones, microsieves (or contact filters), biofilters, plant lagoons, and sludge basins (Jokumsen & Svendsen, 2010, 24-25, 35).

Based on effectiveness of water cleaning, model farms can be divided into types I, II and III although for various reasons (water abstraction, investment costs, etc.) (Jokumsen & Svendsen, 2010, 22) currently only types I and III are in use (table 7). Differences in some important characteristics of three types of Danish model fish farms are shown in table 8.

Type of farm	Model 1	Model 2	Model 3
Pond material	Soil or concrete	Soil or concrete	Concrete
Water recirculation[1] (minimum %)	70	85	95
Water use (maximum l/s)	125	60	15
Fish density (maximum kg/m^3)	50	50	50
Water residence time in production unit (minimum hours)	8.9	12.3	18.5
Maximum daily feeding (kg)	800	800	800
Sludge collection in basins	Yes	Yes	Yes
Decentralized sedimentation (e.g., sludge cones)	Yes	Yes	Yes
Devices for removal of particulate matter	Yes	Yes	Yes
Biofilter	No	Yes	Yes
Plant lagoons (1440 m^2)[2]	Yes	No	Yes

[1] (Internal recirculation flow/(Internal recirculation flow + Water intake)) * 100

[2] Minimum residence time of 9 hours in plant lagoons and a maximum hydraulic load of 1 l per 48 m^2 plant lagoon; average depth 0.7–0.9 m.

Table 8. Important characteristics of three types of Danish model fish farms (Jokumsen & Svendsen, 2010, 21).

Expected removal percentages for BOD and nutrients at different farm types set in the Government Order for Model Trout Farms are listed in the table 9.

	BOD (%)	Total nitrogen (%)	Total phosphorus (%)
Traditional freshwater fish farms	20	7	20
Model trout farm, type 1	70	7	55
Model trout farm, type 2	50	15	45
Model trout farm, type 2 without micro sieves	45	11	40
Model trout farm, type 3	80	15	65
Model trout farm, type 3 without micro sieves	75	11	60

Table 9. Assumed removal percentages for BOD and nutrients at different farm types (Jokumsen & Svendsen, 2010, 22).

Based on this data, farm of type III can be considered the most efficient. Actually, the investigation described by Jokumsen and Svendsen (2010, 33-34) shows that the removal percentages of nutrients and organic matter for several monitored type III model trout farms were significantly higher (table 10) than the assumed figures shown in table 9.

	Total nitrogen	Total phosphorus	BOD
R_N	50%	76%	93%

Table 10. The removal percentages (Rn) of nutrients and organic matter for 8 intensively monitored type III model trout farms (Jokumsen & Svendsen, 2010, 33-34).

However, in spite of being the improved technology for phosphorus reduction, model farming has some environmental and management disadvantages that should be taken into account in environmental management:

- higher energy consumption per kg fish;
- increased discharge of CO2;
- risk of toxic levels of ammonia and risk of disagreeable taste in fish meat;
- increased need in supervision, management and back-up systems: electricity, oxygen, pumps, etc. (Jokumsen & Svendsen 2010, 33).

Since model farming allows suppressing phosphorus losses more effectively than traditional farming, it provides opportunities to increase feeding quotas and volumes of production.

Considering that the organization of a model farm is relatively cheap, one can conclude that this technology has good perspectives of spreading.

6.2.2 Fully recirculated aquaculture (FREA) technology

Fully recirculated agriculture (FREA) also known as RAS (recirculated aquaculture system) is the most advanced technology for removal of nutrients from aquaculture based on thorough cleaning and reuse of water. FREA farms are indoor plants that include the following main units (AquaMaof w.y.):

- fish nursery and fish production tanks;
- water circulation system;
- biological filter system;
- settling tanks;
- drainage system;
- oxygen dissolving system;
- feeding system;
- support systems (electricity / power distribution system, emergency power generator, emergency oxygen supply, compressed air).

A possible scheme for FREA construction is shown of figure 10.

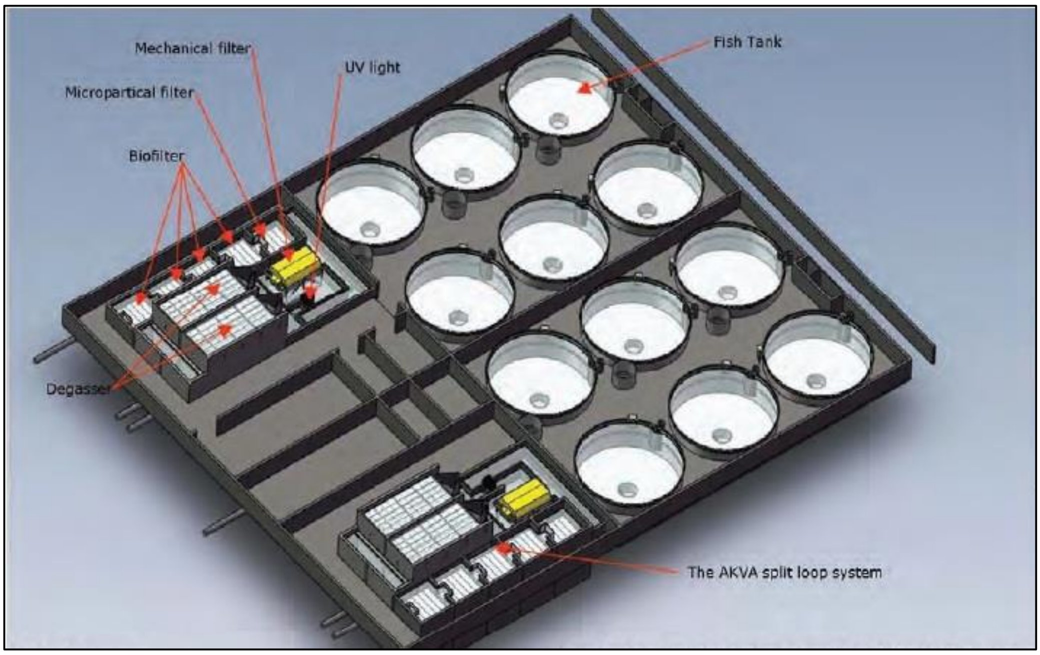

Figure 10. Scheme for FREA farm construction (Jokumsen & Svendsen, 2010, 37)

A source of water for FREA systems is upper groundwater (drain or bore well). Compared to other aquaculture systems, the smallest amounts of water are taken for FREA plants (approximately 7–8 times less than that of a type III model trout farms and 100 times less than that of a traditional farms). Water exchange is supposed to be about 10% of the total water volume per day. It may be possible to achieve a certain re-use of water by taking the water from drains close to the percolation area (Jokumsen & Svendsen, 2010, 37-38).

In the process of water recirculation FREA systems remove phosphates by chemical precipitation or biological processes in combination with denitrification (Murray, Bostock & Fletcher 2014, 17).

However, this closed system cannot be considered absolutely free from phosphorus discharges into environment. Nutrients losses are possible through the water discharged to the percolation zone. Theoretically fish farming at FREA can produce 4 kg of phosphorus per tonne of fish produced, which is similar to the 4.4 kg of phosphorus per tonne of fish found in type III model farms (Jokumsen & Svendsen 2010, 39). According to rough estimations, about 90% of produced phosphorus remains in the sludge but the rest 10% percolate into the root zone plant (into environment). That is why one should consider additional measures (for example, further treatment) to decrease the contents of phosphorus in FREA wastewaters and sludge.

The main obstacle for wide spreading of FREA systems is their price. The systems are expensive to buy and to operate, and typically have higher capital costs than less intensive aquaculture systems (Wheaton, 2008). That is why they can be economically viable only to farming high value species (for example, salmonids) or life-stages in these systems (Murray, Bostock & Fletcher 2014, 44). Murray, Bostock and Fletcher (ibid, 41-43) analyzed costs of salmonid fish (Atlantic salmon) produced with using FREA system in the case of Danish Langsand Lax, the aquaculture farm which began using FREA for commercial producing salmonid fish the first in Denmark.

Since the farm had previous experience in salmon farming, relevant engineering and farming skills, environmental licenses for aquaculture operation, infrastructure and other pre-conditions good for a rapid and on-cost build and availability of a generous government capital investment subsidy, it reduced some costs. Using cost-effective materials and low-cost procurement were preferred as well. Costs items are listed in the table 11.

Estimated operational costs for production of 4.5kg salmon (LWE) from a 1,000t/year capacity salt-water RAS – excluding labour and financing costs (source Langsand Lax)

Item	Price €	Units & unit costs
Smolts (including egg cost)	0.47	125g individual smolt weight
Feed	5.25	€1.15/kg smolt feed: (EFCR 1,05)
Oxygen liquid	0.31	€0.18/kg oxygen
Energy	0.71	€0.10/kg (kWh)
Heating and cooling	0.11	€0.10/kg (kWh - heat pump)
Carbon source	0.26	€0.4/ litre (alcohol)
Iron chloride	0.06	€0.54/ litre
Polymers	0.2	€2.68/ litre
Sludge	0.09	€13.5/ ton removed
Base buffers	0.08	€0.17/kg (lime)
Total	**7.38**	**Per fish @ 4.5 kg mean harvest weight**
Total	**1.65**	**Per kg of fish LWE**

Table 11. Estimated operational costs for production of 4,5 kg salmon from a 1000 ton per year capacity RAS (Murray, Bostock and Fletcher, 2014).

So, production costs were estimated at 1,65 euro/kg for 1000 tonnes/year for basic operational costs rising to 3,10 euro/kg (farmgate dressed head-on bled on ice) including financing, depreciation and all other costs. These costs were estimated to be between 20 - 30% higher than those of "the most efficient" Norwegian salmon farm. Market analyses showed that considerably larger-scale salmon FREA system will be necessary for profitable operation (Murray, Bostock and Fletcher, 2014, 42).

This conclusion is proven to be true by the number of Danish farms that grow salmonid fish using FREA. In Denmark farms of the FREA type are relatively few in number comparatively to the farms of the other types. According to the CHR (CHR, 2015), among the salmonid farms of Denmark that grow fish for consumption using the recirculation technology there are: Danaqua Aps (3 units), Løvlund Dambrug Aps (2 units), Kongeeens Dambrug Aps (2 units), Aquapri Denmark A/S, Bisgerd Dambrug, Frea A/S, Isenvad Fiskeri A/S, Snaptun Frysehus A/S, and Tingkjærvad Dambrug (1 unit for each). However, considering the remarkable share of rainbow trout produced with use of the recirculation technology (figure 8) one can suppose that only large enterprises with large production volumes can afford it. It can thus be concluded that the most obvious way of spreading FREA technology is trout farms enlargement.

7. Conclusions

In Denmark, the phosphorus loading from point sources has decreased over the years. Of the diffuse sources, agriculture remains the main source of phosphorus loading. Agricultural phosphorus demand and the great potential for phosphorus recycling from manure make agriculture one of the key factors in phosphorus pollution reduction. The third Action Plan for the Aquatic Environment (APAE III) focuses in reducing excess phosphorus from agriculture by 50% by 2015. In addition, tools such as P-index could be used.

As for wastewater treatment, Denmark has been able to reduce phosphorus pollution by 85% due to better methods, stricter regulations and decreased industrial discharges. Despite the very high level of wastewater treatment, the municipal wastewater treatment plants still remain the biggest point source of phosphorus pollution. Danish legislation on sludge treatment differs somewhat from that of the EU but for example the removal requirements are in line with the HELCOM recommendations. In terms of small-scale waste water treatment, Denmark is one of the pioneers of the constructed wetland systems that can be used both in wastewater and sludge treatment. Anaerobic digestion technology has proven to be suitable for treating wastewater and waste from different sources. In the process, dewatered sludge, suitable to be used as fertiliser, and biogas are produced.

Aquaculture as an industry is an important and growing sector in Denmark which makes it interesting in terms of phosphorus pollution although the rate of phosphorus loading from aquaculture is relatively low compared to agriculture. The aquaculture industry is regulated by national legislation and the EU Water Framework Directive. From aquaculture sources, phosphorus is discharged as both particulate and dissolved phosphorus into the environment. Especially rainbow trout production forms the biggest risk of phosphorus discharges. The four main technologies have different efficiency rates in phosphorus reduction. In particular, Danish model farming and recirculation-based FREA/RAS technologies have decreased the phosphorus loading from aquaculture.

Phosphorus constitutes a major part of the nutrient pollution in the Baltic Sea region causing eutrophication. As phosphorus is a non-substitutable and non-renewable resource, it needs to be used, reused and recycled in an efficient way. As this report shows, Denmark as one of the major phosphorus polluters in the Baltic Sea region has been proactive in discovering ways to reduce, manage and recycle phosphorus more efficiently.

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