BATTLE ALONG THE RIVER RHINE

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INTRODUCTION

The river Rhine is located in Europe, has a length of 1233 km, a catchment area of 185,260 km^2, and a population of 58 million people who reside around the Rhine.

The Rhine begins in the Swiss canton of Graubünden in the southeastern Swiss Alps, forms part of the Swiss-Austrian, Swiss-Liechtenstein, Swiss-German, and then Franco-German borders. It continues to flow through the Rhineland and the Netherlands, and empties into the North Sea. This report will focus on the downstream part of the Rhine, where it flows through Germany towards the North Sea in the Netherlands.

OBJECTIVE

The objective of this report is to build a real-world, low-dimensional, coupled human-environmental quality model of the Rhine flowing through Germany and the Netherlands. The model will address the following:

1) A simplified Rhine Alarm Model using simplified geometry at steady state.
2) An estimation of the pollution load into the Rhine over time assuming no treatment.
3) A simulation of pollution along the Rhine over generations.
4) A coupled economic growth and environmental quality model for sustainable development.

PART 1 | A SIMPLIFIED RHINE ALARM MODEL

This chapter contains the explanation and steps performed to build a simplified-geometry model at steady state condition for the river Rhine. The Rhine is a not completely mixed system, but rather of an incompletely mixed condition with varying concentrations of substances present within its system boundaries. This system can be represented by serially-connected completely mixed systems. Therefore, the river is divided into four reactors where each has a completed mixed flow, and within each there is decay of the nitrogen pollutant.

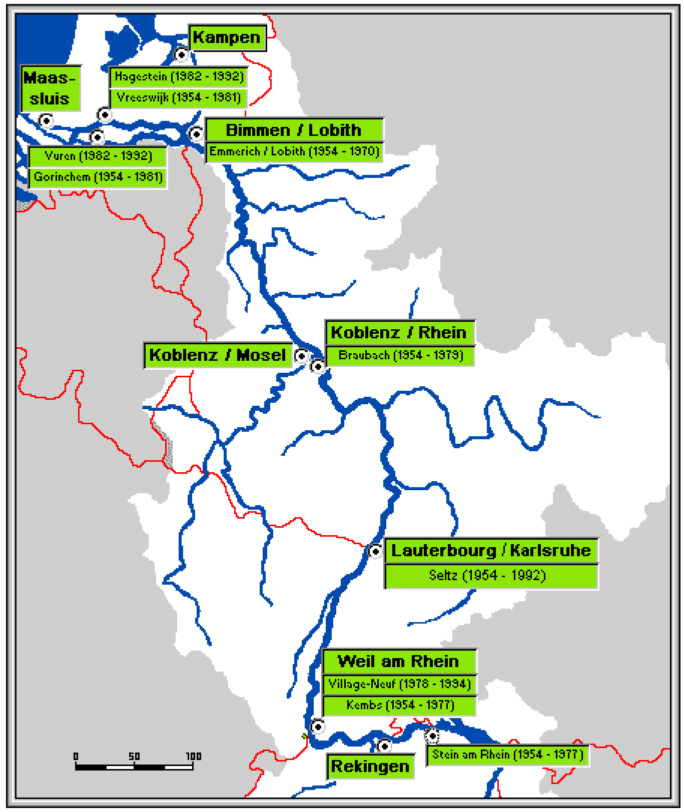

FIGURE 1: RIVER RHINE MONITORING STATIONS

1.1) The Four Considered Reactors

As shown in Figure 1, the four reactors are identified through five measurement stations (in order from upstream to downstream):

1) Strasbourg
2) Lauterbourg
3) Koblenz/Mosel
4) Bimmen/Lobith
5) Maassluis

Table 1 summarizes the hydraulic data at each of the measurement stations. The values are an average of data from the years 2009, 2011, 2013, and 2015.

TABLE 1: MONITORING STATION HYDRAULIC DATA

	1 Strasbourg	2 Lauterbourg	3 Koblenz/Mosel	4 Bimmen/Lobith	5 Maassluis
Q [m³/s]	1002.50	1175.42	303.90	2089.62	1452.03
V [m/s]	2.53	4.04	0.54	3.32	2.30
A [m²]	396	291	563	630	630
C Total-N [mg/l]	2	1.793	3.514	2.922	2.817

Therefore, the four reactors are defined as follows (in order from upstream to downstream):

- Reactor 1: Strasbourg – Lauterbourg
- Reactor 2: Lauterbourg – Koblenz/Mosel
- Reactor 3: Koblenz/Mosel – Bimmen/Lobith
- Reactor 4: Bimmen/Lobith – Maassluis

The lengths of the reactors where measured using Google Earth, the results summarized in Table 2.

TABLE 2: REACTOR LENGTHS

Reactor	1	2	3	4
L [km]	100	243	217	151

1.2) Assumptions Made to Build the Model

The following assumptions were made while building the alarm model for the river Rhine:

1) The cross-sectional area is constant for each reactor, based on the average of the upstream and downstream cross-sections.
2) The discharge for each reactor is constant, based on the average of the upstream and downstream discharges.
3) The total nitrogen present in the river system only comes from the application of fertilizer by the agricultural industry within the river Rhine catchment.

1.3) Estimating Step Loading for Total Nitrogen in the Rhine

The step loading of nitrogen for each reactor of the river Rhine catchment was estimated through the data of pollution load in the Rhine catchment per km^2 of agricultural area. The values are summarized in Table 3.

TABLE 3: RIVER RHINE CATCHMENT CHARACTERISTICS

Catchment	Land Area [10^4 km^2]	Avg. Q [km^3/yr.]	Pop. Density [person/ km^2]	Agriculture Land [%]	DIN Load [10^{-3} ton]
River Rhine	16.45	58.47	300.35	45.99	361.97

Therefore, the yearly Dissolved Inorganic Nitrogen (DIN) Load in kg for 1 km^2 is calculated as follows:

$$\frac{DIN\ Load\ (10^3\ ton)}{Area\ (10^4\ km^2)} = \frac{361.97\ \times 10^3\ ton}{16.45\ \times\ 10^4\ km^2} \times\ 1000 = 2200.43 \frac{kg}{km^2}/year$$

An estimation of the extent of the agricultural area in the analyzed catchment was made using Table 5 in the paper “Nitrogen in the environment, by J.L. Hatfield, R.F. Follett, 2001”; see Table 4.

TABLE 4: LAND USE IN THE RHINE CATCHMENT

						Agricultural area			
	Total area[1]	Urban area		Forest area		Arable land		Grass land	
Country	×1000 km^2	×1000 km^2	%	×1000 km^2	%	×1000 km^2	%	×1000 km^2	%
CH	34	3	9	11	33	5	15	14	41
D	102	22	22	40	39	27	26	13	13
L	2.6	0.3	12	0.9	35	0.5	21	0.7	27
F	23	1.3	6	8.8	40	5.9	27	5.0	23
NL	24	7	31	2	9	4	16	9	36
TOTAL	188	34	18	63	34	42	23	42	22

CH: Switzerland; D: Germany; L: Luxembourg; F: France; NL: The Netherlands.
[1]Note that total area does not equal the sum of urban, forest, and agricultural areas. This is due to both uncertainties in area estimates and the fact that other, less-important forms of land use is not included in the table.

Only arable land is considered as the agricultural area where fertilizer is applied, as summarized in Table 5.

TABLE 5: ARABLE LAND AREA BY COUNTRY

	Netherlands	Germany
Arable Land [km^2]	4000	27000

The nitrogen loading affecting each reactor is generated from its respective arable land. Therefore, to estimate the step loading for each reactor, for Germany the arable land was partitioned further among the reactors. The basis of the partitioning was the total nitrogen concentration value provided by each measuring station. The estimated arable land partitioned for each reactor was determined to be the area required to yield the measured value of nitrogen concentration for the reactor.

The final obtained values used in the model are summarized in Table 6.

TABLE 6: REACTOR VALUES FOR MODEL

	Reactor 1 (Germany)	Reactor 2 (Germany)	Reactor 3 (Germany)	Reactor 4 (Netherlands)
Extension of Arable Land [%]	20%	50%	30%	100%
Arable Land [km^2]	5400	13500	8100	4000
W [kg/s]	0.377	0.942	0.565	0.279
W [mg/s]	376712.329	941780.822	565068.493	279046.169

1.4) Equation Developed for the Model

Based on the principles of conservation of mass, and the interconnection of completely mixed systems, an equation was developed for the model to compute the total nitrogen in the river Rhine.

Figure 2 shows a differential element within which the conservation of mass is applied. It represents the approach used with each of the four reactors while applying the principles of conservation of mass to them.

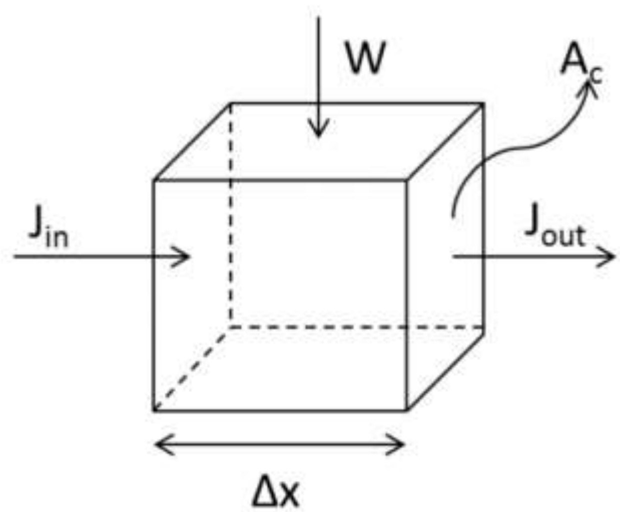

FIGURE 2: CONSERVATION OF MASS

Using the principle of the mass conservation, an equation for the computation of the nitrogen concentration was developed:

$$\left(C_{in_i} \times Q_i\right) - (C_i \times Q_i) + W_i - k \times V_i \times C_i = 0$$

Where:

Cin_i = input concentration in the reactor I [mg/kg]

Q discharge [m3/s]

W step loading [mg/s]

K, decay value = 0,18[d^-1] = 2.138*10^(-6) [s^(-1)]

V_i volume [m3]

$$C_i = \frac{W_i + (C_{ini} \times Q_i)}{Q_i + k \times V_i}$$

1.5) Rhine Alarm Model for Total Nitrogen Concentration

Using the equation from the previous section, the model was created using Python, generating the output:

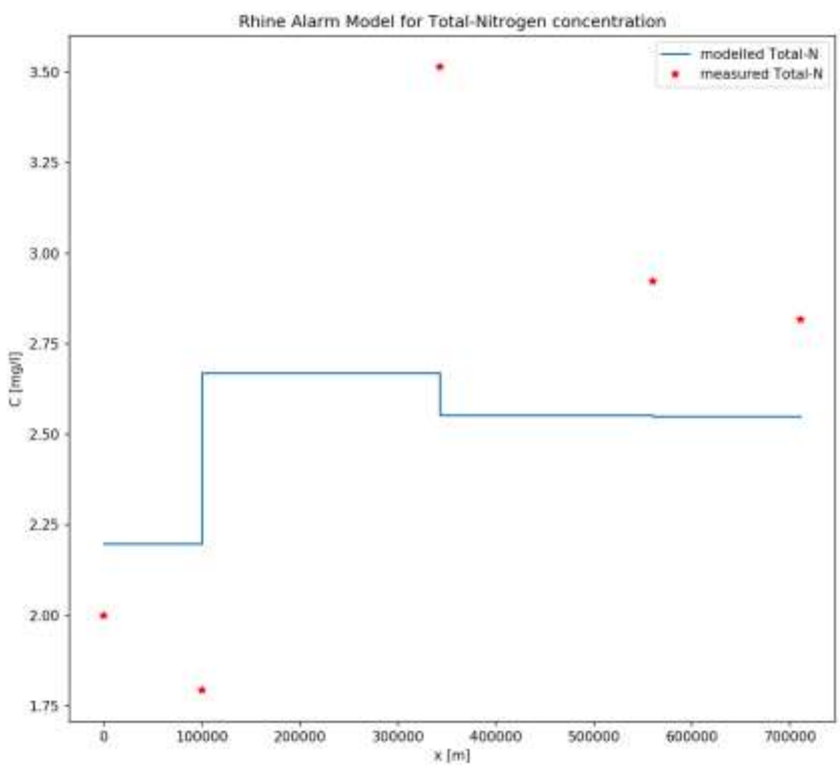

FIGURE 3: PYTHON OUTPUT FOR RHINE ALARM MODEL

PART 2 | ESTIMATION OF POLLUTION LOAD INTO THE RHINE OVER TIME

The improvement of water quality in the river Rhine system is of paramount importance to the condition of its ecosystem. Since 1970, organic pollution has decreased by 80%, and the organic load has also reduced substantially. However, for continued improvement of water quality, a further reduction of diffuse inputs of pollutants and nutrients into waters via agricultural origin are required. The pertinent water quality problem of the Rhine catchment is the concentration of nitrogen, and subsequently the risk of river eutrophication. [source: ICPR].

The Rhine's monitored value of total nitrogen would be in violation of the quality standard indicated in the Environmental Protection Agency (EPA) Directive for Surface Water (74/440/EEC, Parameter standard for water quality, reported by EPA). The Directive limits the maximum concentration of nitrate in surface water to be drinkable to 25 mg/L, according to the European Environmental Agency. This corresponds to a total concentration limit of nitrogen to approximately 10 mg/L. However, the Dutch standard total nitrogen concentration limit is 2.2 mg/L: This value will be the threshold to indicate high water quality in the river system. A natural indicator of high water quality is the presence of wild Atlantic salmon.

The river Rhine is historically linked with the Atlantic salmon. Until the 18th century, the Rhine was the most prominent salmon river in Europe (ICPR, 2004). However, the decrease in river Rhine's water quality negatively affected the salmon population, which is vulnerable to high concentrations of nutrients and pollutants in its habitat.

Looking at the values of total nitrogen measured by different stations (an average of the years 2007-2015), the concentration exceeds the Dutch standard mostly during the winter and autumn months. Conversely, between June and September the concentration falls below the threshold value.

TABLE 7: AVERAGE CONCENTRATION OF TOTAL NITROGEN

Monitoring Station	Yearly Average of Total Nitrogen [mg/l]
Lauterbourg/Karlsruhe	1.79
Koblenz/Mosel	3.51
Bimmen/Lobith	2.92
Maassluis	2.82

For implementation of the socio-hydrological model, an average value of 2.76 mg/l is used as the representative value of total nitrogen in the river Rhine.

To achieve the threshold of 2.2 mg/l, two processes are considered. First is dilution of the total nitrogen concentration through a process activated by the introduction of precipitation into the system. The total nitrogen concentration in rainwater is estimated to be 0.28 mg/l, indicated in Table 8 as the average value.

TABLE 8: NITROGEN CONCENTRATION IN RAINWATER

Date	Time[1]	Elapsed Time	Rate of Collection	Rainfall Intensity	Volume of Sample	Total Rain for Day	Total N[2] NH_4-NO_3-N	N/min	Na[3]	Cl[4]
		min	cm^3/min	mm/h	cm^3	cm	mg/l	g/min	mg/l	mg/l
3/11/53	9: 34—9: 37	3	220	13.2	660		.16	35.2		
	9: 38 3 4									
	9: 43 1/2	4—3/4	97	5.9	460	1.19	.11	10.6		
3/27/53	14: 24—14: 27	3	188	11.3	566	.47	.08	15.1		
4/22/53	14: 45—15: 10	25	38	1.8	740		.51	15.1	2.8	4.8
	15: 12—15: 43	31	23	1.4	715		.39	9.0	1.4	3.0
	15: 44—15: 55	11	65	3.9	720		.10	6.6	.6	.6
	16: 08—16: 25	17	35	2.1	591		.24	8.4		
	16: 28—17: 30	62	11	.7	707	.35	.66	7.5	2.0	2.0
							Av=.28			

The amount of rainwater necessary to restore 1 km of length of river Rhine is 2.55*10^8 liters. This value was determined through a mass balance calculation, based on the volume of water in 1 km length of the river Rhine. The average width of the river is 450 m, and the average water depth 4.5 m, yielding an approximate volume of 9*10^8 liters of water per 1 km of river length.

The second process involves maintenance of the river banks and the alarm river system, such as monitoring and enforcement to deter illegal discharges to the river. To carry out these tasks, 3 workers are needed for the entire river length.

A restored length of the river Rhine is a nursery for 7000 to 21000 adult salmon. (source: Salmon population in restore condition). Therefore, there are an estimated 8000 salmon for Rhine's water corresponding to the high water quality total nitrogen concentration value of 2.2 mg/l.

TABLE 9: X-VALUES OF MODEL

	Lx (Labor)	Kx (Water, L)	X (Salmon)
Point 1	3	255000000	8000
Point 2	9	83000000	8000

Lx = labor workers

Kx = liters of water required to dilution process

X = salmon population

Rainwater for environmental use conflicts with its use for agricultural purposes. In the model schematization, rainwater is used for irrigation of the arable land in the Rhine catchment. Therefore, the production of food is at odds with the increase of environmental quality due to their competing with each other over the same resource: water.

When considering food production, only the arable land that produces cereals and grains are considered, because this is the most common agricultural product of the Rhine catchment. On average, the harvested production of cereals per square meter is 0.75 kg in Germany (Source: DB Source), and the amount of water needed is 674.3 liters per m^2 (Source: unwater.org), and the labor required is 0.0013 persons/m^2 (Source: DB Source, Farm Type).

Therefore, the values for the model are established to be:

TABLE 10: Y-VALUES OF MODEL

Ky	Ly	Y
0.0013	674.3	0.75

Next, the amount of food produced (y) is kept constant, and the amount of water is reduced by half. The reduction of water will result in an increase in the labor which will increase by 3 times the current value. Therefore, this iteration yields the following values:

TABLE 11: ADJUSTED Y-VALUES OF MODEL

Ky	Ly	Y
0.0039	337.15	0.75

2.1) Production function set – Environmental Quality

The two points provided above are used to calibrate the general production function of environmental quality:

$$X = A(K_x)^{\alpha} \times (L_x)^{(1-\alpha)}$$

A and α are factors dependent on the effectiveness of technology, and the estimation of their values will be executed during the calibration process.

Thus, the following two equations are obtained:

- $8000 = A(2.55 \times 10^{8})^{\alpha} \times 3^{(1-\alpha)}$
- $8000 = A(8.3 \times 10^{7})^{\alpha} \times 9^{(1-\alpha)}$

Where *A* and α have values of 0.319 and 0.494, respectively. Therefore, the environmental quality function is:

$$X = 0.319 \times {K_x}^{0.494} \times {L_x}^{(1-0.494)}$$

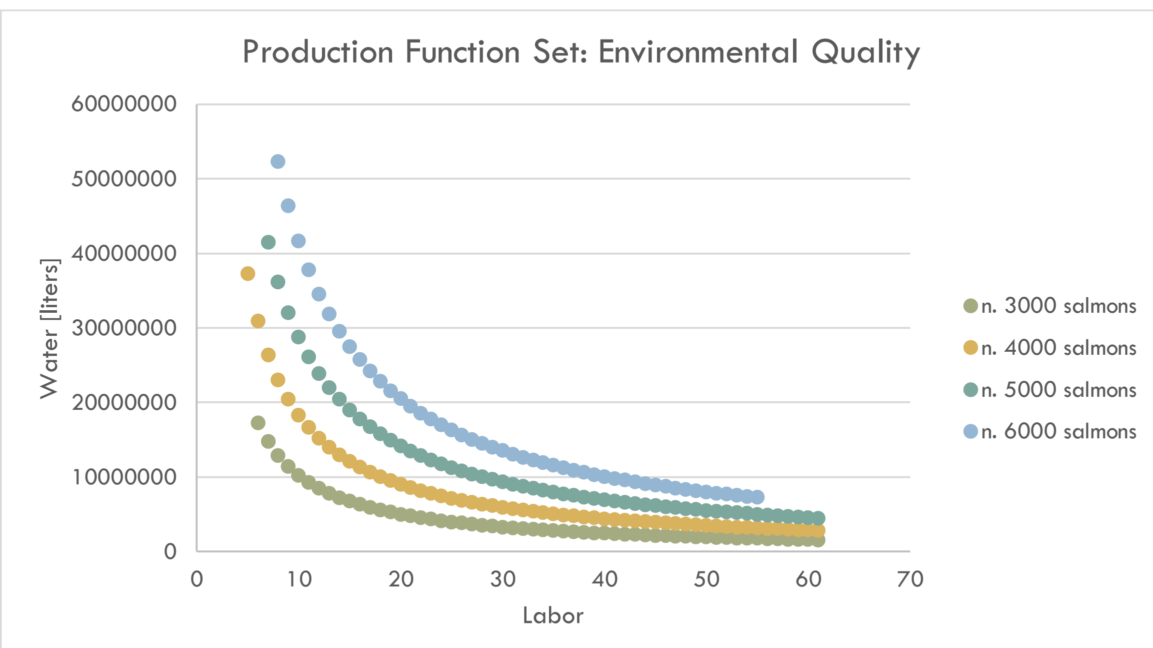

FIGURE 4: PRODUCTION FUNCTION SET - ENVIRONMENTAL QUALITY

2.2) Production function set – Food

The two points provided above are used to calibrate the general production function of food production:

$$Y = A(K_y)^{\alpha} \times (L_y)^{(1-\alpha)}$$

A and α are factors dependent on the effectiveness of technology, and the estimation of their values will be executed during the calibration process.

Thus, the following two equations are obtained:

- $0.75 = A(674.3)^{\alpha} \times 0.0013^{(1-\alpha)}$
- $0.75 = A(337.15)^{\alpha} \times 0.0039^{(1-\alpha)}$

Where A and α have values of 0.184 and 0.613, respectively. Therefore, the food production function is:

$$Y = 0.184 \times K_y{}^{0.613} \times L_y{}^{(1-0.613)}$$

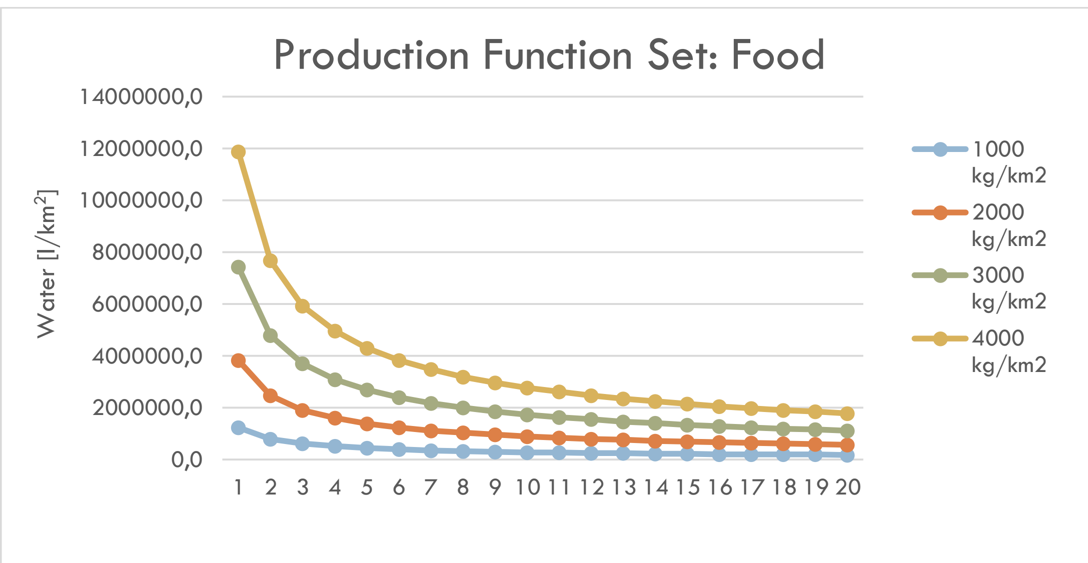

FIGURE 5: PRODUCTION FUNCTION SET - FOOD

2.5) Production Possibility Frontier

To obtain the production possibility frontier (PPF), the two production function sets (food and environmental quality) are plotted on the same graph with diagonally opposite origins in an Edgeworth Box (Figure 6). The points of tangency (Table 12) between the curves yield the *(x, y)* coordinates of the PPF (Figure 7).

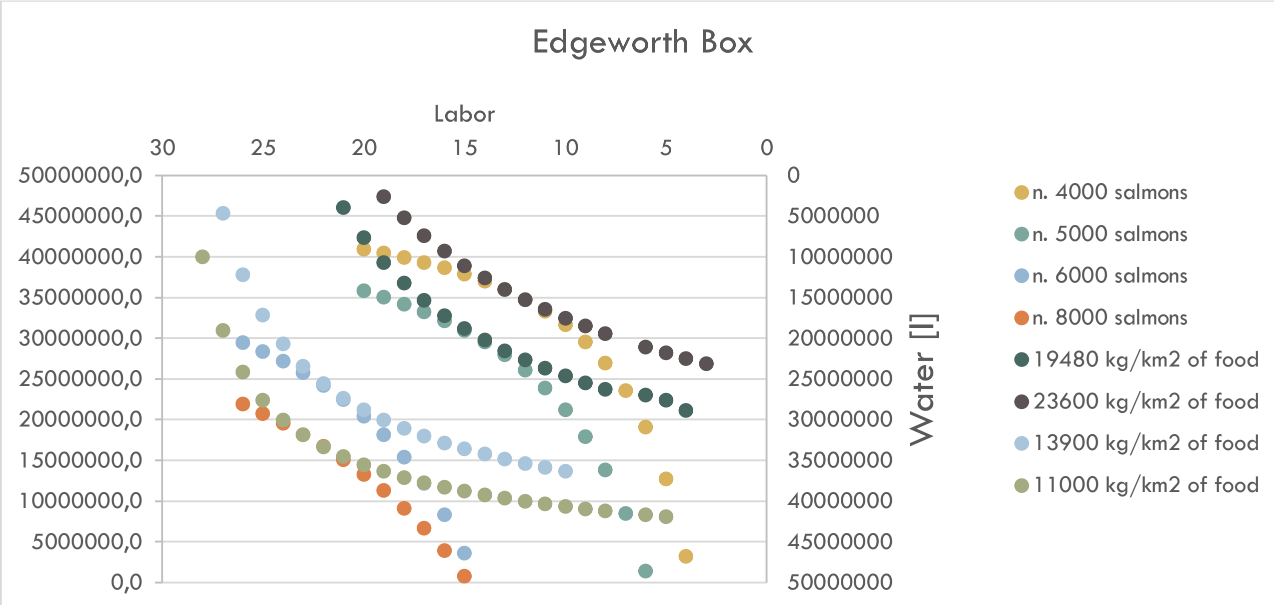

FIGURE 6: EDGEWORTH BOX

TABLE 12: POINTS OF TANGENCY

Environmental Quality	Food
X	Y
4000	23600
5000	19480
6000	13900

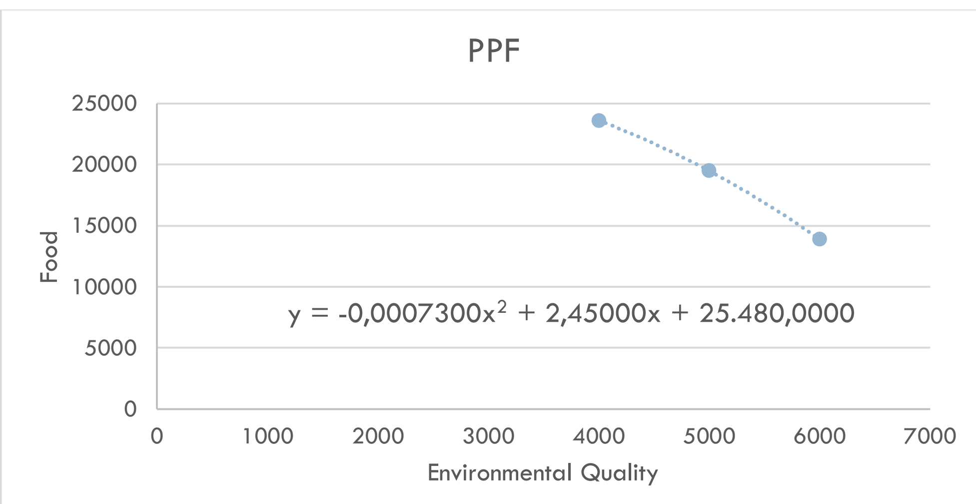

FIGURE 7: PRODUCTION POSSIBILITY FRONTIER

The quadratic trend line yields the PPF equation:

$$y = -0.00073x^2 + 2.45x + 25480$$

The general equilibrium problem can be solved mathematically through the Lagrange derivation:

$$\mathcal{L} = \ln(C_1) + \eta \ln(C_2) - P_1(C_1 - x) - P_2(C_2 - y) - \lambda(y + 0.00073\, x^2 - 2.45\, x - 25480)$$

In the optimization: C_1 and C_2 are maximized; P_1, P_2, and λ are minimized; and η is assumed to have a value of 1. This means that society weighs the consumption of the two goods equally. Thus, the optimum point is determined to be:

$$(x, y) = (3410.87, 25342.37)$$

However, the resulting apparent mathematic resolution does not reveal a utility function curve tangent to the PPM curve. Therefore, a point indicated as $(x, y) = (4500, 21722.5)$ is taken in consideration to define the utility function. This point was picked through an estimation of the utility value.

$$u = \ln(C_1) + \eta * \ln(C_2)$$

$$u = 18.39$$

$$P_1 = \frac{1}{C_1} = 0.000222$$

$$P_2 = \frac{1}{C_2} = 4.60352 \times 10^{-5}$$

$$M = 2\ (budget) = P_1 \times C_1 + P_2 \times C_2$$

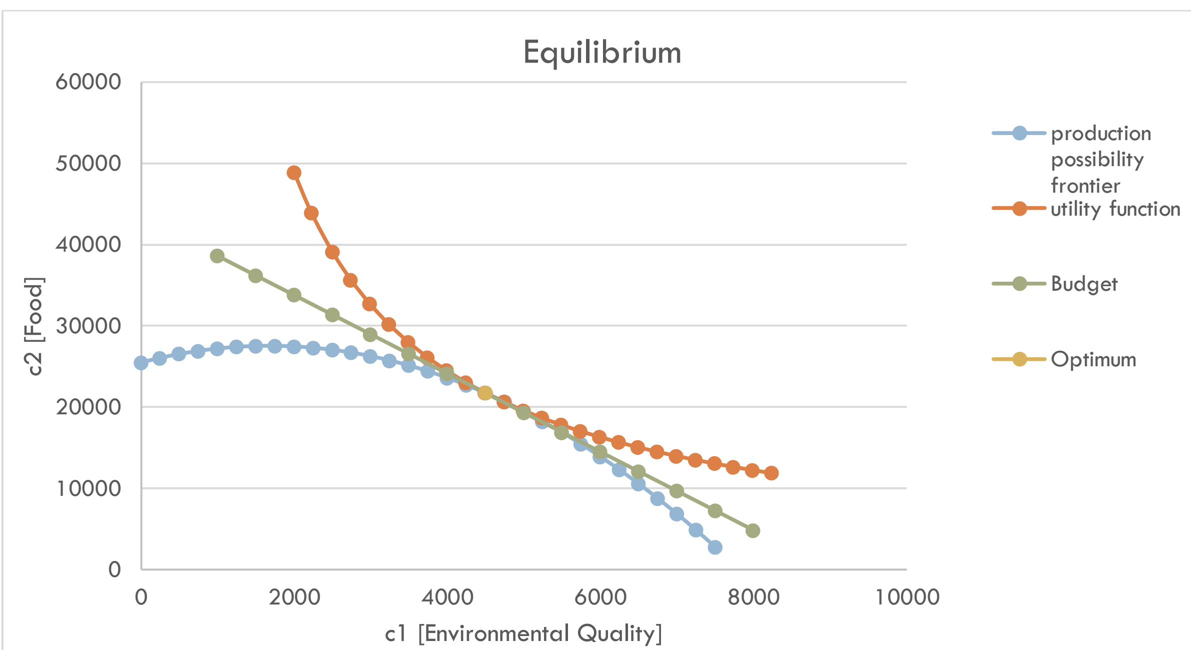

FIGURE 8: EQUILIBRIUM OF PPF AND UTILITY FUNCTION

From 0.75 kg/m^2 (750000 kg/km^2) of food production, the load per km^2 is equal to 2200.04 kg/km^2/year.

Now the food production is equal to 21722.5 kg/m^2, it is assumed that the load is increased by X10.

Therefore, the estimated production of 21722.5 kg/m^2 food yields a nitrogen load for agricultural practice (use of fertilize) is determined: 22000.04 kg/km^2/year is equal to 0.00698 kg/km^2/sec.

TABLE 13: LOADING RATE FOR EACH REACTOR

%	1	0.3	0.5	0.2
	Reactor 4	Reactor 3	Reactor 2	Reactor 1
W [kg/s]	2.7905	5.6507	9.4179	3.7671

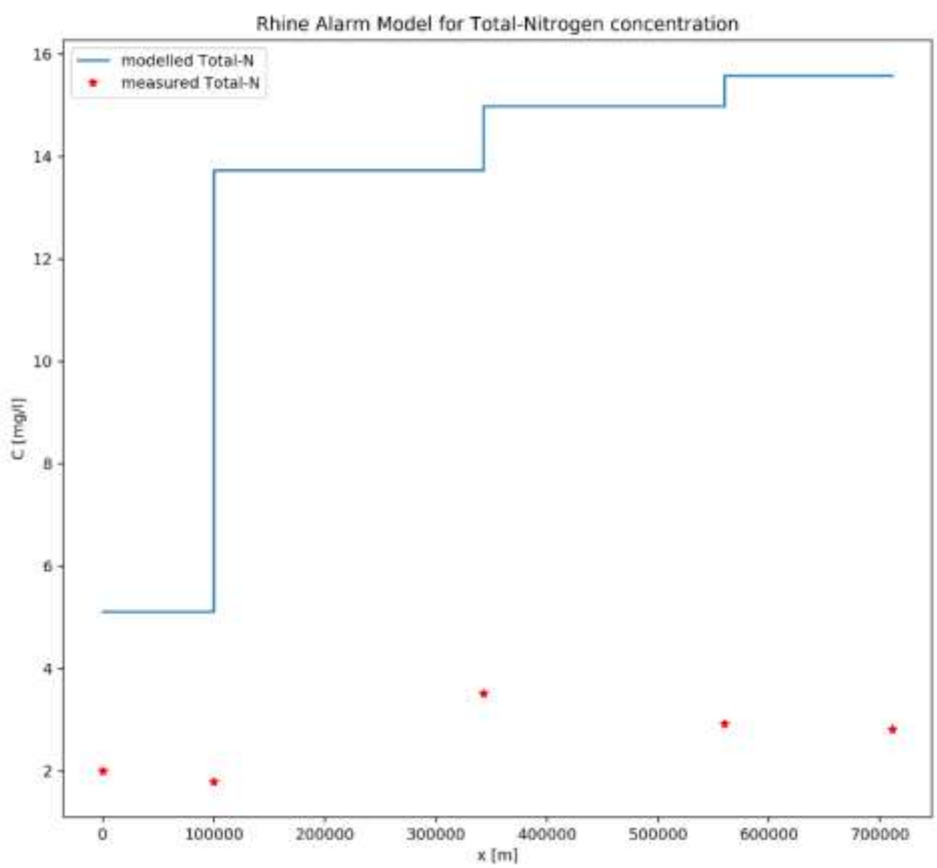

FIGURE 9: RHINE ALARM MODEL FOR TOTAL NITROGEN CONCENTRATION

PART 3 | SIMULATING POLLUTION ALONG THE RHINE OVER GENERATIONS

A simulation of the total nitrogen concentration in the river Rhine was computed through implementation of the river alarm model, introducing data that referred to past and future generations.

3.1) Simulation for the Past Generation

For the past generation, an elaboration was made using the average concentration of the total nitrogen in measuring station 1 for the year 2007. Thus, C_{in} = 2.5 mg/l for the past generation.

Concerning the step loading in each reactor, an increase of 40% was estimated. Table 14 summarizes the new values of the step loading as used for modeling the past generation.

TABLE 14: VALUES FOR STEP LOADING IN EACH REACTOR, PAST GENERATION

Past Generation	Reactor 1	Reactor 2	Reactor 3	Reactor 4
W [kg/s]	0.5274	1.3185	0.7911	0.3907

The distribution of the total nitrogen concentration for the past scenario is shown in Figure 10.

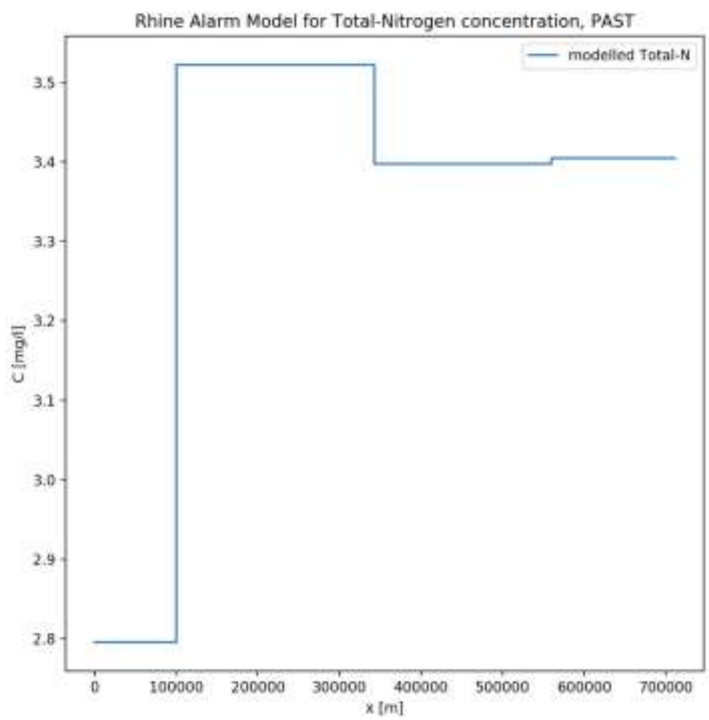

FIGURE 10: DISTRIBUTION OF TOTAL NITROGEN, PAST GENERATION

3.2) Simulation for the Future Generation

For the future generation, C_{in} was estimated to be equal to 1.5 mg/l and the step loadings in each reactor were decreased by 30%, the final values used in modeling the future scenario are presented in table …

This estimation is based on the future measures that ICPR wants to implement facilitate reduction of the diffuse nutrient inputs of agricultural origin, and subsequently reduce the concentration of nitrogen and phosphorous compounds in the water bodies. Table 15 summarizes the new values of the step loading as used for modeling the future generation.

TABLE 15: VALUES FOR STEP LOADING IN EACH REACTOR, FUTURE GENERATION

Future Generation	Reactor 1	Reactor 2	Reactor 3	Reactor 4
W [kg/s]	0.2637	0.6592	0.3955	0.1953

The distribution of the total nitrogen concentration for the future scenario is shown in Figure 11.

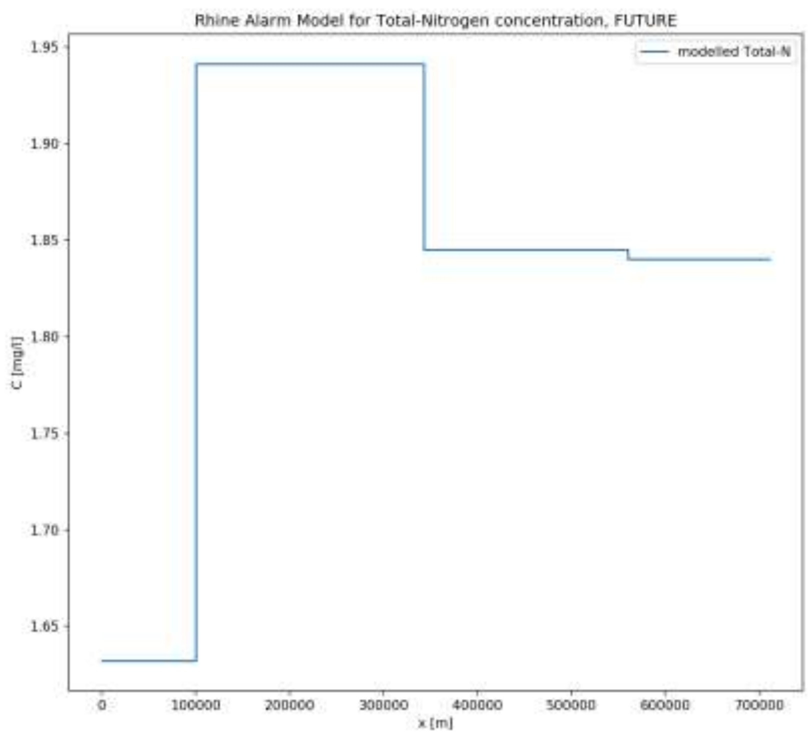

FIGURE 11: DISTRIBUTION OF TOTAL NITROGEN, FUTURE GENERATION

3.3) Role of Technology

Looking at the production function:

$$x = A * Kx^{\alpha} * lx^{1-\alpha}$$

productivity

returns to scale

dependency from technology

A and alpha are parameters dependent on the level of technology.

The impact that they have on the PPF depends on which direction the technology was developed.

A new technology leading to a decrease in fertilizer consumption and hence, to a more efficient use of the resources, leads to a crush of the curves on the x-axis and his moving up. This means that both food and Environmental Quality increase (case A).

On the other hands, a new technology leading to a decrease in water consumption without any changes in the food production, leads to only a crush of the curve on the x-axis. This means that food does not change and Environmental Quality, instead, increase (case B).

FIGURE 12: IMPACT ON THE PPF, CASE A AND B

4) Public Policy

When there is no balance between social and private needs, the public authority can intervene to regulate the market in order to change the equilibrium point between utility and productivity.

In the case of study, the use of fertilize in the agricultural area of the Rhine catchment, is responsible of the high concentration of nitrogen compounds, impacting negatively the water quality. This results in a serious damage of the ecosystem functions of the river. These functions are cultural (esthetic and cultural recreation), supportive of the native species and economical (fishing activity, water supply).

Therefore, in order to decrease the discharge of nitrogen, the imposition of a tax on fertilize consume can led to (effective change of the equilibrium point)water quality improvements

For the estimation of the damage related to nitrogen pollution, the total profit from the diadromous fishing in the river was used. Indeed, the diadromous fishes (Atlantic salmon fits into this category),are sensible to high concentration of nutrients.

The Eurostat database service reveals that Germany earn 61,095,103 euro from Aquaculture production in 2010.

The most important areas of interest for inland fisheries are: the Lakes of Brandenburg and Mecklenburg, the Lake Constance, the Elbe, the Havel, the Rhine and the Mosel rivers.

The 35 % of the fishing cached comes from the river Rhine. [fisheries in Germany, Directorate- General for internal policies, European parliament, 2014]

While in Netherlands, 25,500,000 is the total income for the market of diadromous fishes from aquaculture production and the 60% comes from the river Rhine.

Consumption of fertilize per hectare in Germany is equal to 219 kg per hectare of arable land in 2010 World bank data [http://data.worldbank.org/indicator/AG.CON.FERT.ZS?name_desc=false].

While the Netherlands is equal to 335 kg per hectare of arable square (estimation for 2010 from world bank data http://data.worldbank.org/indicator/AG.CON.FERT.ZS?name_desc=false).

In the build of the marginal utility function we made the assumption that it is equal for Netherlands and Germany.

The marginal utility function is the derivative of the utility function. It is decreasing as express the utility that the population has for amount of product consumed, which is going to decrease slowly at the increase of the consumption.

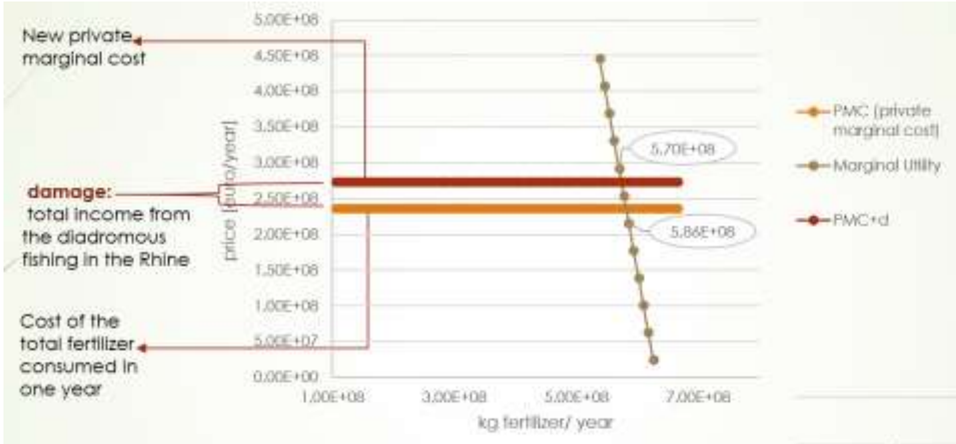

FIGURE 13: POLICY ANALYSIS

The result of taxes is a decrease in the fertilizer production of 3%. This leads to a decrease in the food production, with a shift of the equilibrium point on the right (higher environmental quality).

However, looking at the consumption of fertilizer, Germany consumes 219 kg/km2/year while the Netherlands 355 kg/km2/year. At a large scale, instead, is the Germany that discharge more Nitrogen in the Rhine (5.94*10^7 kg/year).

This analysis can indicate a different utility from the use of fertilizer between the two nations.

The construction of the utility function for each nation, reveals that the application of an equal tax leads to a high reduction of fertilizer production for Germany which results in a reduction of food production. This reduction does lead only to a small improvement in the water quality.

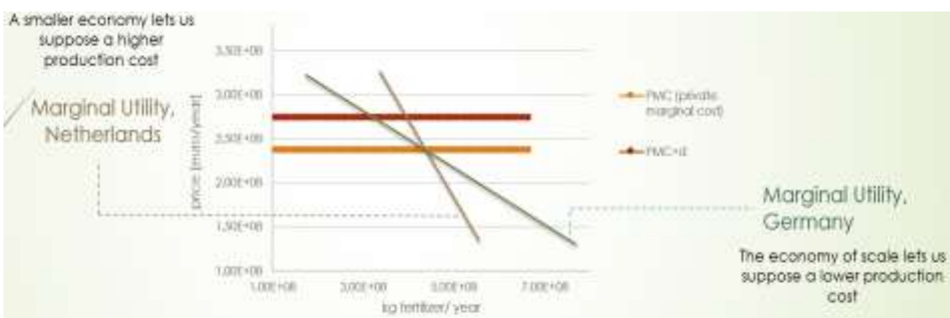

FIGURE 14: POLICY ANALYSIS, TWO DIFFERENT UTILITY FUNCTIONS

Therefore, a different tax values is suggested for Germany and the Netherlands, in order to control the use of fertilize and therefore, the nitrogen pollution in the river.