Optimization of Industrial Wastewater Disposal into Rivers (Case Study: Ohio River).

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Abstract:

Linear programming serves as a vital operational research technique for optimizing various scenarios. It finds application in managing industrial waste disposal into rivers when considering environmental concerns. This methodology aids in making informed decisions regarding waste disposal by addressing the concerns of multiple stakeholders. Within this framework, industrial priorities are translated into "objective functions," aiming to "Minimize the amount of reduced pollution load" with 3 major constraints. These constraints include stream standard constraints, effluent standards constraints, and wastewater treatment standards constraints. Through linear programming modeling, the optimal conditions are determined, delineating the requisite level of wastewater treatment each industry must undertake before discharge, thereby safeguarding the river from pollution**.**

Keywords: Biochemical Oxygen Demand (BOD), Optimization, Effluent, Wastewater, Environmental Protection Agency (EPA)

Introduction

When it comes to industrial wastewater disposal into rivers, there exists a conflict between two factors. Industries prioritize maximizing profits, which entails minimizing expenses related to waste processing, as waste processing directly correlates with expenditure. Conversely, river management authorities, in this case, EPA advocate for minimal pollution loads from industrial and other sources to uphold the quality of river water and prevent pollution.

Resolving the above dilemma requires balancing the interests of both parties: minimizing industrial waste processing costs while ensuring that discharged waste does not compromise water quality standards. Mathematical models, such as linear programming, can aid in decision-making by providing a structured approach to this complex problem.

My work will explore how Linear Programming can be utilized to enhance wastewater disposal practices in rivers, thereby aiding river water management. Discharging wastewater into rivers can lead to a decline in water quality. To mitigate this, industries must minimize pollution loads by managing waste, such as through the construction and operation of wastewater treatment facilities before disposal into rivers.

To support the discussion, take the Ohio River as a study case. The Ohio River is an important water source for the state of Ohio and the United States with over 10 tributaries. As raw water for a water treatment plant, the quality of the Ohio River must be protected from pollution.

At present, the Ohio River is one of the country's most polluted rivers, serving as a disposal site for various industrial and domestic waste types. More than 30 small to large industries are located along the Ohio River and its tributaries causing some of this pollution into the river and the state wants to reduce it.
The state in its effort to reduce the pollution on the river has set up a committee to develop an optimization model aimed at optimizing the point source pollution into the Ohio River. The committee identifies industries along the Ohio River as the heaviest point source of pollutants (spilling wastewater into the river) and decided to get a model that will help determine the minimum amount of pollutant spill into the river in other to maintain the safe use of the river and also prevent the industries from running loss (treating the wastewater).

Method

The formulation of linear programming models in this case refers to the interests of both parties, i.e. industry (as the party that is obliged to treat the wastewater) and regulator (EPA) (as the party responsible for controlling water pollution). Industry expectations are lower treatment costs, while the regulator and river operator do not want river pollution. In this linear programming, industry expectations will be "objective function", namely "Minimizing treatment cost" or "Minimizing the amount of reduced pollution load. This can also be written as "Maximize the pollution load that is discharged into the river". The main constraint of this function is river water quality (represented by the BOD (Biochemical Oxygen Demand) parameter).

Model 1:

I used 3 industries for the initial model, the data used is from the EPA website. The data includes the BOD of river water, river flow, BOD of industrial wastewater depending on each industry's category, and wastewater flow. The total industry is 3 units (Table 1), consisting of 2 industries that directly dispose of wastewater into the Ohio River and 2 industries that dispose of wastewater into the Cumberland River (a tributary of the Ohio River). In this modeling, the Cumberland River is a point source to the Ohio River. Hence, the number of point sources is 3 units.

Fig. 1

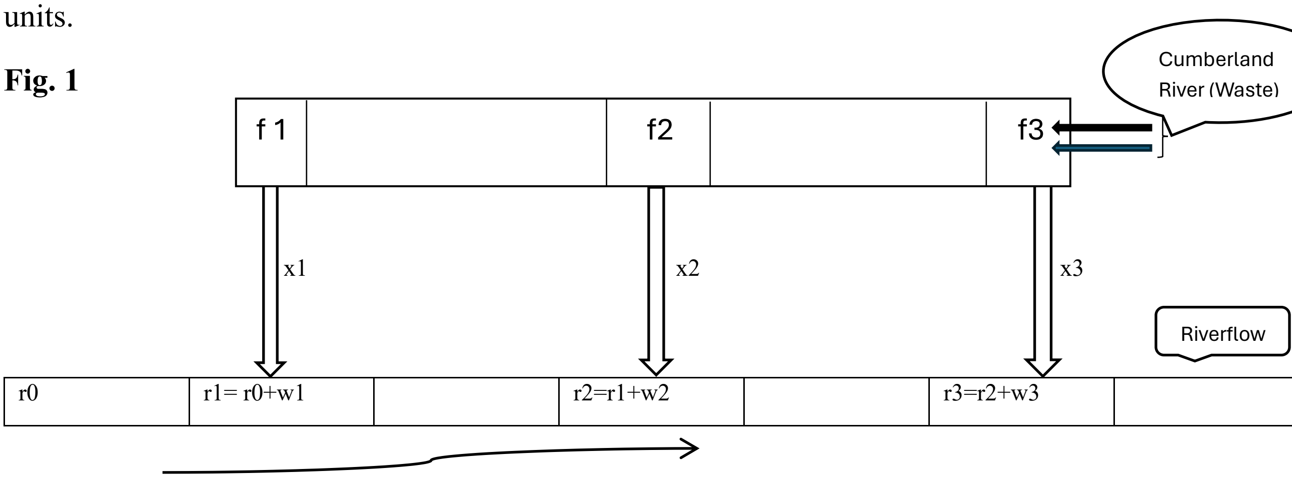

Fig. 1: Sketch of industrial waste discharge into the Ohio River
Remarks:

$f1 \ldots f3$ = Pollution load of wastewater before treatment kg/day at industry (1...3)
$r0 \ldots r3$ = River flow
$x1 \ldots x3$ = pollution load of wastewater after treatment at industry (1 ... 3)
$w1 \ldots w3$ = Wastewater flow at industry (1 … 3)
C = BOD along the river
$f = r * c/100$
S = stream quality standards
e = effluent quality standards

Fig 1 shows the flow of the river from one point to the other, the flow changes any time there is a discharge by industries into the river as shown above.

Based on the description, data the linear programming model is formulated as follows:

Maximize:

$y = x1 + x2 + x3$

Constraints:

Stream Standards Constraints (BOD of all water discharge into the stream at each flow level should not be more than the stream BOD standard set by EPA)
1. $1000(I + x1) / r1 <= S$
2. $1000(I + x1 + x2)/r2 <= S$
3. $1000(I + x1 + x2 + x3)/r3 <= S$

Effluent Standard Constraints (Each industry wastewater discharge should not be more than the industry BOD set by the EPA)
4. $1000*x1/w1 <= e1$
5. $1000*x2/w2 <= e2$
6. $1000*x3/w3 <= e3$

Treatment Standard Constraint (Pollutants in the wastewater after treatment should be less than pollutants in the wastewater before treatment).
6. $x1 <= f1$
7. $x2 <= f2$
8. $x3 <= f3$

Explanation:
The objective function (maximize $y = x1 + x2 + x3$) is to maximize the pollution load in the wastewater after treatment. This represents the interest of the industries, that is at each point in time, the industries will want to reduce the amount of treatment of wastewater since it will reduce their expenditure.

The stream standard constraints indicate the required BOD level of waste water allowable in the stream and it is calculated by the EPA as follows:
1000(Initial pollution load + waste water spillage by industries into the river after treatment)/The river flow level at each point of discharge, and it should be less than or equal to S (the BOD standard set by EPA).

The Effluent Standard Constraints represent the amount of BOD level in wastewater each industry is allowed to spill into the river. It is calculated by,
1000*(pollution load of wastewater after treatment by each industry)/wastewater flow level of each respective industry and it should be less than or equal to ei (the effluent standard of the respective industry set by EPA.
The treatment standard constraints indicate that at each point of discharge by each industry, the pollution load in wastewater after treatment (xi) should be less than or equal to the pollution load of wastewater before treatment (fi).

Table 1: Point Source Pollution Data of the Ohio River

No	**Industry**	**Flow (r) m3/day**	**BOD (c) mg/L**	**Pollution Load (f) Kg/day**	**Effluent Standard BOD (mg/L)**
1	Steel and Aluminum Industry (Ray)	12325.2	142.67	1758.4	100
2	Petrochemical Plants (PA)	6409.3	133.6	856.3	50
3	Industry along the Cumberland River	22172.5	299.67	6644.4	150

Source: EPA website and some calculations

Results and Explanation

The solution to the above model begins by entering all known values such as the effluent standards, stream quality standards, etc.
With the help of Ampl software used for this project, optimal results are obtained. The modeling results for the above problem can be seen in Fig. 2.

The output shows the pollution loads that can be disposed of by each industry. Based on the results all industries must reduce the wastewater load before disposing into the Ohio River. The percentage of treatment for each industry can be seen in Table 2.

NB: The percentage of treatment is dependent on the type of industry and the amount of pollutant containing in their waste water (eg. An Oil Refinering company may have a higher percentage of treatment as compare to a Beverage Company).

Fig. 2. The Ampl Solution for the model 1

```
ampl: reset;
ampl: model project1.mod;
ampl: solve;
CPLEX 22.1.1.0: optimal solution; objective 2112.52
0 dual simplex iterations (0 in phase I)
ampl: display x;
x [*] :=
company1   618.03
company2    17.395
company3  1477.1
;
```

Table 2. Industries Pollution Load Reduction (By Calculations Base on the Model)

Industries	**Initial Pollution Load By Industries (kg/day)**	**Allowed Pollution Load Based on the Model (kg/day)**	**Pollution Load Reduction (kg/day)**	**Percentage % of Industrial Treatments (kg/day)**
1	1758.4	618.0	1140.37	64.9
2	856.3	17.4	838.9	97.5
3	6644.4	1477.1	5167.3	77.7

Model 2:

Model 2 is an expansion of model 1, Since am looking at all industries that spill wastewater into the Ohio River, I increased the point source to 8 industries to check the efficiency of the model.

Objective function:

Maximize:

y = sum {i in companies} x [i]

```
subject to stream_constraint {k in companies}:
1000*(I + sum {i in 1...k}x[i])/(r[k]) <= S.
subject to effluent_standard_contraint {i in companies}:
1000*x[i]/w[i] <= e[i]
subject to treatment_standard {i in companies}:
x[i] <= f[i]
```

Data:

Table 3: Point Source Pollution Data of the Ohio River

No (i)	Industry	Flow (r) m3/day	BOD (c) mg/L	Pollution Load (f) Kg/day	Effluent Standard (e) BOD (mg/L)	Wastewater Flow-of (w)
1	Steel and Aluminum Industry (Ray)	12325.2	142.67	1758.4	100	6180.3
2	Petrochemical Plants (PA)	6409.3	133.6	856.3	50	347.9
3	Industry along the Cumberland River	22172.5	299.67	6644.4	150	9847.3
4	Steel and Aluminum Industry (Mill)	24500.6	61.2	1500.4	100	1980.2
5	Oil Refinery Plant (Orgill)	25067.9	49.3	1235.3	45	567.3
6	Beverage Industry (Magg Depot)	15191.3	36.9	560.4	100	123.4
7	Petrochemical Plants (Glue)	31925.8	177.74	5674.5	50	6734.5
8	Beverage Industry (Brew)	12071.1	13.7	665.7	100	145.3

Result and Explanation

Again, optimal results are obtained with the help of Ampl software used for this project. The modeling results for the above problem can be seen in Fig. 3.

The output shows the pollution loads that each industry can dispose of. Based on the results all industries must reduce the wastewater load before disposing into the Ohio River. The percentage of treatment for each industry can be seen in Table 4.

Fig. 3. The Ampl Solution for the model 2

```
ampl: reset;
ampl: model project2.mod;
ampl: solve;
CPLEX 22.1.1.0: optimal solution; objective 2810.7235
0 dual simplex iterations (0 in phase I)
ampl: display x;
x [*] :=
1   618.03
2    17.395
3  1477.1
4   198.02
5    25.5285
6   123.4
7   336.725
8    14.53
```

Table 4. Industries Pollution Load Reduction (By Calculations Base on the Model)

Industries	**Initial Pollution Load By Industries (kg/day)**	**Allowed Pollution Load Based on the Model (kg/day)**	**Pollution Load Reduction (kg/day)**	**Percentage % of Industrial Treatments (kg/day)**
1	1758.4	618.0	1140.37	64.9
2	856.3	17.4	838.9	97.5
3	6644.4	1477.1	5167.3	77.7
4	1500.2	198.0	1302.2	86.8
5	1235.3	25.5	1209.8	97.9
6	560.4	123.4	437	77.9
7	5674.5	336.7	5337.8	94.1
8	665.7	14.53	651.17	97.8

Model 3:

Model 3 is an expansion of model 2, I taking into consideration all industries that spill wastewater into the Ohio River. At the moment we are looking at over 35 industries spilling waste water into the Ohio River with direct point source being 30 for this project.

```
set companies := 1 .. 30;

param I; #initial pollution load in the river kg/day

param S := 950; #stream quality standard(BOD)

param e{i in companies}; #effluent quality standard for company i

param f{i in companies}; # pollution load of wastewater from company i before
treatment

param w{i in companies}; #wastewater flow-of in company i

param r{i in companies}; #river flow m^3/day (r1=r0+w1, r2=r1+w2,....

var x{i in companies} >= 0; #pollution load of wastewater from company i
after treatment

maximize pollution_load: sum{i in companies} x[i];

subject to stream_constraint{c in companies}:

1000*(I + sum{i in 1..c}x[i])/(r[c]) <= S;

subject to effluent_standard_contraint{i in companies}:

1000*x[i]/w[i] <= e[i];

subject to treatment_standard{i in companies}:

x[i] <= f[i];
```

Data:

Table 5: Point Source Pollution Data of the Ohio River

No (i)	Flow (r) m3/day	BOD (c) mg/L	Pollution Load (f) Kg/day	Effluent Standard (e) BOD (mg/L)	Wastewater Flow-of (w)
1	12325.2	142.66	1758.4	150	6180.3
2	12673.1	67.58	856.3	70	1347.9
3	22520.4	295.04	6644.4	100	9847.3
4	24500.6	61.23	1500.1	100	1980.2
5	14123.9	87.46	1235.3	145	867.3
6	20191.3	27.75	560.4	250	1123.4
7	11925.8	475.82	5674.5	50	6734.5
8	23071.1	28.85	665.7	150	1145.3
9	17590.5	32.11	564.8	80	1309.2
10	21680.5	34.39	745.7	185	1060.9
11	19545.1	63.23	1235.8	190	2067.1
12	11195.5	178.78	2001.5	200	903.2
13	11020.5	81.77	901.2	175	1623.7
14	10178.2	82.00	834.6	190	1348.0
15	13690.3	36.16	495.0	95	790.5
16	22340.4	11.64	260.1	150	1280.3
17	11450.1	65.55	750.6	160	1540.7
18	13061.8	59.76	780.6	50	1060.5
19	15790.1	336.96	5320.6	145	9705.3
20	17430.1	23.65	412.3	120	1750.1
21	16215.2	82.96	1345.2	245	2254.8
22	15023.1	108.51	1630.1	150	2145.0
23	19182.3	33.41	640.9	270	1560.2
24	13801.0	161.59	2230.1	190	3890.1
25	15503.2	100.02	1550.6	185	5230.2
26	12089.1	81.90	990.1	100	2201.2
27	15902.5	166.07	2640.9	150	4554.9
28	21209.1	54.23	1150.2	155	3350.2
29	12001.9	71.22	854.8	145	1145.6
30	14502.0	52.413	760.1	160	1230.3

Result and Explanation

Again, optimal results are obtained with the help of Ampl software used for this project. The modeling results for the above problem can be seen in Fig. 4.

The output shows the pollution loads that each industry can dispose of. Based on the results all industries must reduce the wastewater load before disposing into the Ohio River. The output provide in details the allowable pollutant for each specific industry after treatment.
The percentage of treatment and reduction load for each industry can be seen in Table 6.

Fig. 4. The Ampl Solution for the model 3

```
CPLEX 22.1.1.0: optimal solution; objective 11505.6275
0 dual simplex iterations (0 in phase I)
ampl: display x;
x [*] :=
 1  927.045     7  336.725    13  284.147    19 1407.27     25  967.587
 2   94.353     8  171.795    14  256.12     20  210.012    26  220.12
 3  984.73      9  104.736    15   75.0975   21  552.426    27  683.235
 4  198.02     10  196.267    16  192.045    22  321.75     28  519.281
 5  125.759    11  392.749    17  246.512    23  421.254    29  166.112
 6  280.85     12  180.64     18   53.025    24  739.119    30  196.848
```

Table 6. Industries Pollution Load Reduction (By Calculations Base on the Model)

Industries	Initial Pollution Load By Industries (kg/day)	Allowed Pollution Load Based on the Model (kg/day)	Pollution Load Reduction (kg/day)	Percentage % of Industrial Treatments (kg/day)
1	1758.4	927.045	831.355	47.28
2	856.3	94.353	761.947	88.98
3	6644.4	984.73	5659.67	85.18
4	1500.1	198.02	1302.08	86.80
5	1235.3	125.759	1109.541	89.82
6	560.4	280.85	279.55	49.88
7	5674.5	336.725	5337.775	94.07
8	665.7	171.795	493.905	74.19
9	564.8	104.736	460.064	81.46
10	745.7	196.267	549.433	73.68
11	1235.8	392.749	843.051	68.22
12	2001.5	180.64	1820.86	90.97
13	901.2	284.147	617.053	68.47
14	834.6	256.12	578.48	69.31
15	495.0	75.0975	419.9025	84.83
16	260.1	192.045	68.055	26.16
17	750.6	246.512	504.088	67.16
18	780.6	53.025	727.575	93.21
19	5320.6	1407.27	3913.33	73.55
20	412.3	210.012	202.288	49.06
21	1345.2	552.426	792.774	58.93
22	1630.1	321.75	1308.35	80.26
23	640.9	421.254	219.646	34.27
24	2230.1	739.119	1490.981	66.86
25	1550.6	967.587	583.013	37.60
26	990.1	220.12	769.98	77.77
27	2640.9	683.235	1957.665	74.13
28	1150.2	519.281	630.919	54.85
29	854.8	166.122	688.678	80.57
30	760.1	196.848	563.252	74.10

Observations

From the results of all the model (1-3) you will realize that the reduction load and percentage of treatment for each industry keep changing, this is because the model takes into consideration the waste water flow of each industry and allowable BOD levels require by each industry. As the point of source (industries in this case) increases the river flow increases which increases the pollution load in the river and hence affect the treatment require by each industry along each flow of the river.

Conclusion

Decision-making under specific limitations can involve converting the problem into a linear function and addressing it through linear programming models. For instance, in managing wastewater discharge into a water source, linear programming enables decision-making regarding the necessary waste treatment levels for each industry. By integrating criteria like stream and effluent quality standards, an optimal solution can be reached. It's advised that for effective utilization of linear programming in water quality management, comprehensive data pertaining to water quality should be available, as it significantly influences both the model outcomes and decision-making. In this project, the committee can advise the state on the projects result as to what amount of BOD level allowable into the river to maintain the EPA standards and also maintain minimum cost to the industries involve for a win win for all.

Acknowledgment

Acknowledgments to ***Melkonian Vardges***, for quiding me through this projects and helping me with new directions and resolution of some issues I was having with my Ampl code.

Future Directions

This project only considered the Ohio River as a case study but offcos we have a lot of rivers in the US across states, I would love to extend this project to combinations of rivers in the US and increase the point source in other to help maintain river safety across all states.

Also this project didn't look into the degradation of microorganism along the river that may discompose some of this pollutants resolvng in a reduction of the pollutants along the river because of data constraints. It is important to study the degradation level along the river for some time in other to come up with good degradation coefficient to add to the model, since it is affected by a lot of things. This is something I may want to look into in the future and see how the results may be affected.

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