OPTIMIZATION MODEL FOR ALLOCATION OF POLLUTANT LOADS FROM NON-POINT SOURCES IN WATERSHED USING GIS

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Abstract— A method is developed to optimize the allocation of pollutant loads from non-point sources in a watershed by combining the application of optimization theory and GIS technique. The study area is modeled as a watershed with land use map and digital elevation model by ArcView GIS. Using calculated values of flow length from each land management unit (LMU), in the study area, to the outlet and area of each LMU, and assumed value of watershed-wide self-purification coefficient, a linear programming model is formulated. The objective function maximizes total allowable discharged pollutant loads from LMUs in the study area subject to the constraints of effluent limitation at the outlet of the watershed, i.e., study area, relation among mean effluents from different LMUs, and minimum limit of effluent in each LMU. Optimization is carried out at different weight values depending on decision-maker's preference order of LMU type with respect to mean load discharged from unit area. The developed model is applied to a sub-catchment of Yasu river basin in Shiga prefecture, Japan, which demonstrates the model's ability to determine optimum allocations of discharged loads of total nitrogen from different types of LMUs in the sub-catchment.

I. Introduction

The water quality in rivers, lakes and estuaries has been deteriorating due to excessive use of water resources and disposing of drainage without due care. In the past, researches mainly focused on quantitative conservation of water, but recently qualitative conservation has also drawn researchers attention and emphasis is also being given to qualitative aspects of water resources [1], [8]. Water bodies receive pollutants from point sources and/or non-point sources. Point sources are easily identifiable and have known discharged volume, hence they are relatively easier to manage [5]. On the contrary, non-point sources (e.g., agricultural and domestic) are comparatively difficult to manage due to their wide spatial distribution. Moreover, regulations regarding the upper limit of pollutant from these sources are yet to be defined.

In recent years, several researchers have conducted their research in the direction of analyzing and estimating pollutant from non-point sources [10], [3], [4], [5], and its role in the development of water quality management plan for watershed [6]. But less research has been done for deriving optimal management policies for controlling pollutant loads from non-point sources using optimization theory. Randhir *et al.* [7] developed a multi-objective dynamic spatial optimization algorithm using biophysical simulation models AGNPS (Agricultural Nonpoint Source) and EPIC (Erosion Productivity Impact Calculator) and Geographic Information Systems (GIS). However, they considered only agricultural watershed and they also did not take into account the decay factor, which plays important role as the pollutants are transported along their courses. Hence, there is a need to look into related issues more deliberately.

In this study, a method is developed to optimize the allocation of discharged pollutant load from non-point sources in a watershed by combining optimization theory and GIS technique. The use of GIS facilitates easy handling and computations involving data on parameters that have wide spatial variations. GIS is a computer system capable of spatially representing data on the land surface and linking additional data, related to this spatial depiction, through tables and charts. To demonstrate the applicability of developed model, it is applied to a study area in Shiga prefecture, Japan, for determination of an optimum allocation of discharged loads of total nitrogen from various land management units (LMUs).

II. Methodology

A. Computation using ArcView GIS

For this study, data on flowlength and area of each LMU under various landuse type is needed. Geographical data are generally available in the form of Digital Elevation Model (DEM), in raster format; and thematic maps in vector format. To obtain the needed data on flowlength and area, the available geographical data needs to be processed using GIS software tools. In this study, modeling of study area is done using the Spatial Analyst module of ArcView GIS [2]. For this purpose, DEM, in raster format, and landuse map, in vector format, are used. The DEM, used here, has grid size of 50m $\times$ 50m and consists of data on the elevation at center of each grid. In this modeling process, firstly, watersheds

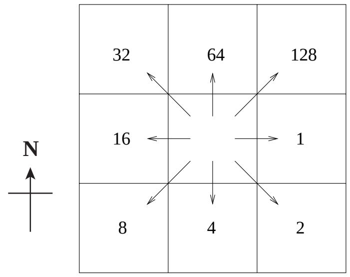

Fig. 1. Flow direction values as given by ArcView

in a relatively larger river basin that includes study area, are delineated from the DEM. A watershed is an area draining water to a common outlet as concentrated drainage. All the sinks in DEM of delineated watersheds are filled then, in order to avoid draining of runoff from grids into each other and thus entering the process into a loop. Sink is defined as a grid having elevation lower than all its surrounding grids or two grids flowing into each other and thus having internal drainage instead of draining into a neighboring grid. From filled DEM of delineated watersheds, the flow direction for each grid is determined using the concept of the steepest slope to one of its eight neighboring cells (Fig. 1). In the resulting grid theme, the central grid takes one out of the eight numbers indicating the flow direction. Based on the value of flow direction, the value of flow accumulation is calculated for each grid. Flow accumulation for a grid is defined as the number of upstream grids flowing into that grid. On the basis of flow accumulation values, the stream networks and thus the outlet of watersheds are determined. Grid cells with a high value of flow accumulation are areas of concentrated flow and are used to identify stream channels. Then out of these derived watersheds, one watershed, whose outlet drains into a permanent river, is chosen as a study area in order to exclude the effect of the river flow on transport of pollutants. For the selected study area (sub-watershed), the flowlength from each grid to the outlet is determined based on the flow direction values. Using the values of flowlength from each grid, average length of flow path for each LMU is computed. The study area is fragmented into LMUs which are polygons of landuse data. The area of each LMU is also derived from landuse map using ArcView GIS.

B. Optimization Model

The pollutants released from non-point sources are first transferred to the streams and later transported along the stream or river. During their transfer from sources to the streams, the pollutant loads normally reduce in amount due to self-purification characteristic of watershed. This reduction can be assumed to be a function of the distance traveled. The reduction rate per unit length can be assumed to be proportional to the amount of discharged pollutant load from sources ($dL/dx = -\lambda L$), and can be integrated to the form $L = L_0 e^{-\lambda x}$. On the basis of these facts, the objective function and constraints for the optimization of discharged pollutant load from non-point sources can be formulated as:

$$\text{Maximize} \quad \sum_{i=1}^{I_p} A_{p_i} L_{p_i} + \sum_{i=1}^{I_d} A_{d_i} L_{d_i} + \sum_{i=1}^{I_f} A_{f_i} L_{f_i} + \sum_{i=1}^{I_c} A_{c_i} L_{c_i} \tag{1}$$

subject to:
(i) Effluent limitation at the outlet of the watershed

$$\sum_{i=1}^{I_p} e^{-\lambda x_{p_i}} A_{p_i} L_{p_i} + \sum_{i=1}^{I_d} e^{-\lambda x_{d_i}} A_{d_i} L_{d_i} + \sum_{i=1}^{I_f} e^{-\lambda x_{f_i}} A_{f_i} L_{f_i} + \sum_{i=1}^{I_c} e^{-\lambda x_{c_i}} A_{c_i} L_{c_i} \leq \overline{L} \tag{2}$$

(ii) Relations among mean effluents from different types of LMUs

$$\frac{\sum_{i=1}^{I_p} A_{p_i} L_{p_i}}{\sum_{i=1}^{I_p} A_{p_i}} = \alpha \frac{\sum_{i=1}^{I_d} A_{d_i} L_{d_i}}{\sum_{i=1}^{I_d} A_{d_i}} \tag{3}$$

$$\frac{\sum_{i=1}^{I_p} A_{p_i} L_{p_i}}{\sum_{i=1}^{I_p} A_{p_i}} = \beta \frac{\sum_{i=1}^{I_f} A_{f_i} L_{f_i}}{\sum_{i=1}^{I_f} A_{f_i}} \tag{4}$$

$$\frac{\sum_{i=1}^{I_p} A_{p_i} L_{p_i}}{\sum_{i=1}^{I_p} A_{p_i}} = \gamma \frac{\sum_{i=1}^{I_c} A_{c_i} L_{c_i}}{\sum_{i=1}^{I_c} A_{c_i}} \tag{5}$$

(iii) Lower limit of effluent in each LMU

$$L_{p_i} \geq L_{p_i}^l \qquad i = 1, 2, \ldots, I_p \tag{6}$$

$$L_{d_i} \geq L_{d_i}^l \qquad i = 1, 2, \ldots, I_d \tag{7}$$

$$L_{f_i} \geq L_{f_i}^l \qquad i = 1, 2, \ldots, I_f \tag{8}$$

$$L_{c_i} \geq L_{c_i}^l \qquad i = 1, 2, \ldots, I_c \tag{9}$$

where p, d, f, and c = indices denoting paddy fields, dry fields, forests, and cities, respectively, i = number of a LMU ($i = 1, 2, \ldots, I$), A_i = area of LMU i (m^2), L_i = discharged pollutant load from LMU i (g/m^2/month), x_i = average length of flow path for LMU i to the outlet (m), λ = watershed-wide self-purification coefficient (m^{-1}), $\overline{L}$ = effluent standard value of pollutant at the outlet of the watershed (g/month), L_i^l = lower limit of pollutant load in LMU i (g/m^2/month), and α, β, and γ = weights. The values of α, β, and γ depend on the preference of decision-maker's, or administrators in water quality management agencies, for LMU type regarding mean

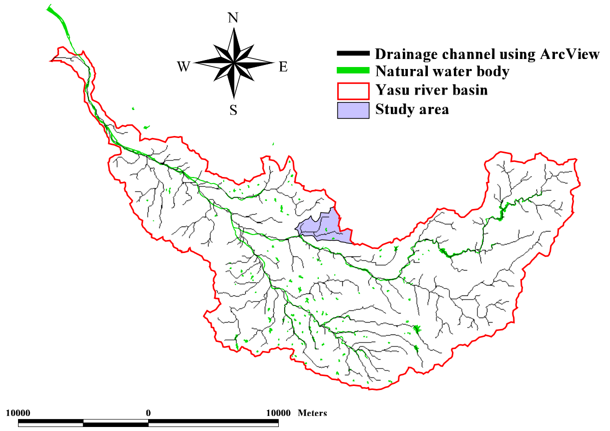

Fig. 2. Map showing the Yasu river basin

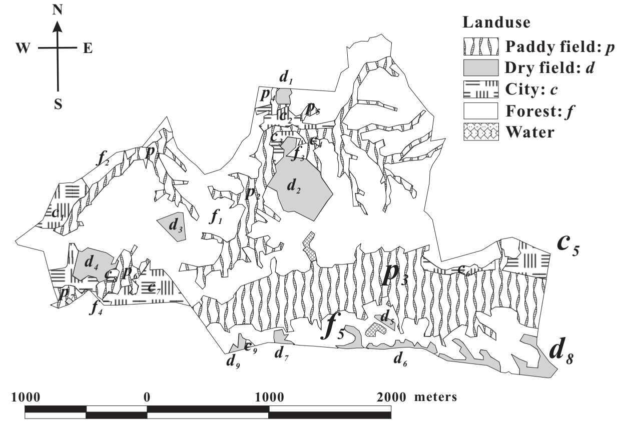

Fig. 4. Landuse and defined LMUs for study area

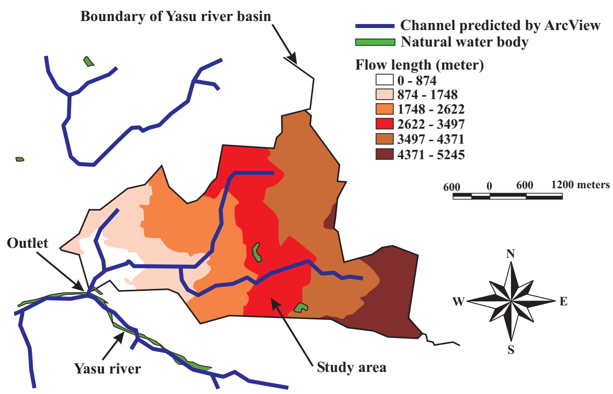

Fig. 3. Flow length for study area

load discharged from an unit area. The linear programming problem, described above, is solved with the different sets of α, β, and γ, to determine the optimum amount of discharged pollutant load (L_i) that can be allocated to each LMU.

III. Application

A. Study area

A sub-watershed of Yasu river basin in Shiga prefecture (Japan), having an area of 6.3 km^2, is selected as the study area (Figs. 2 and 3). The Yasu river basin is one among the larger basins that finally drains into Biwa Lake. Biwa Lake is the largest lake in Japan and serves as a source of drinking water for the inhabitants in the region. The runoff from the selected sub-watershed drains directly into the Yasu river. Dark black line, in Fig. 2, represents the channel networks predicted by ArcView and light black color line represents the natural water body, including river. It is observed that channel networks extracted by ArcView match the natural channel networks most often. The flow length calculated for study area, using GIS, is shown in Fig. 3. The darker bands in the figure represent higher values of flow length and the lighter bands represent lower values of flow length. The landuse pattern in the study area is shown in Fig. 4. The area is dominated by forests and paddy fields mainly. In this area, there are altogether 30 LMUs including 7 units of paddy fields ($p_1 \sim p_7$), 5 units of forest ($f_1 \sim f_5$), 9 units of cities ($c_1 \sim c_9$), and 9 units of dry fields ($d_1 \sim d_9$) (Fig. 4). Therefore, 30 decision variables (one for each LMU) are considered in the objective function and constraints (1)-(9).

B. Optimization

Out of the possible indicators, only T-N (Total Nitrogen) is considered as a pollutant type in this study. The value of λ for T-N is assumed 0.0001 m^{-1} on the basis of study of [3]. The effluent standard value of pollutant at the outlet of watershed ($\overline{L}$) can be decided by a management model of river water quality. However, due to unavailability of such model for the region at moment, it is calculated using values of the unit loading factor [9] for landuse types and total area attributed to different landuse polygons. The values of unit loading factor used for estimating the value of $\overline{L}$ in this study are 0.38 g/m^2/month (paddy fields), 0.77 g/m^2/month (dry fields), 0.034 g/m^2/month (forests) and 0.11 g/m^2/month (cities). The calculated value of $\overline{L}$ used here is 1,294,406.46 g/month. Initially, the values of α, β, and γ are considered as 0.5, 10 and 3, respectively. The preference order, in this case, is assumed as PO1 defining the order: "1) Dry field 2) Paddy field 3) City 4) Forest". The lower limit of allocated discharged pollutant loads in (6)-(9) is set to 0 g/m^2/month in each LMU.

The above optimization problem is solved using the simplex method. The optimum solution obtained is shown in Fig. 5. It is observed that LMUs having higher values of flow length in each landuse type (p_3, f_5, c_5, and d_8) get higher value of discharged pollutant load allocated. Those LMUs, which have lower flow length, get lower limit of discharged pollutant load allocated. Optimum discharged pollutant loads for LMUs p_3, f_5, c_5, and d_8 are 0.939, 0.329, 1.175 and 5.928 g/m^2/month, respectively. All other LMUs have the optimum discharged pollutant load value of 0 g/m^2/month. In Fig. 5, it can be observed

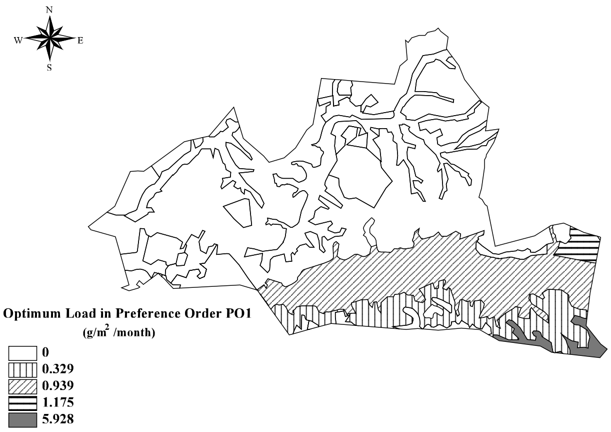

Fig. 5. Optimum allocated pollutant loads for preference orders PO1

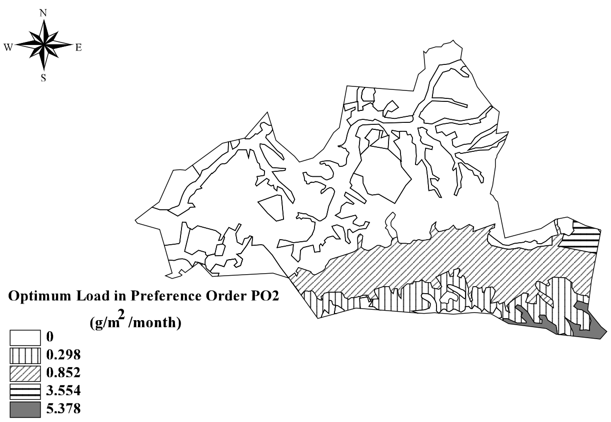

Fig. 6. Optimum allocated pollutant loads for preference orders PO2

that despite the preference order PO1 (paddy field LMUs getting higher preference than city LMUs), the optimum discharged pollutant load value for p_3 is less than that of c_5. This can be attributed to the fact that total area of paddy fields (p_3) is larger than that of city (c_5). The total discharged pollutant load from all the LMUs, i.e., the value of objective function in this solution, is 1,889,498 g/month.

When the preference order is changed from PO1 to PO2 "1) Dry field 2) City 3) Paddy field 4) Forest", by changing the value of γ to 0.9, the optimum values of discharged pollutant load change. In the latter case, the optimum discharged pollutant allocation inclines towards city LMU as compared to paddy field LMU (Fig. 6), and then LMUs p_3, f_5, c_5, and d_8 get the optimum discharged pollutant load values of 0.852, 0.298, 3.554 and 5.378 g/m^2/month, respectively. Also in this case, all other LMUs have optimum value of discharged pollutant load as 0 g/m^2/month. It is observed that optimized values of allocated pollutant load are sensitive to the preference order of LMU. The total discharged pollutant load from all LMUs in this case is 1,897,985 g/month.

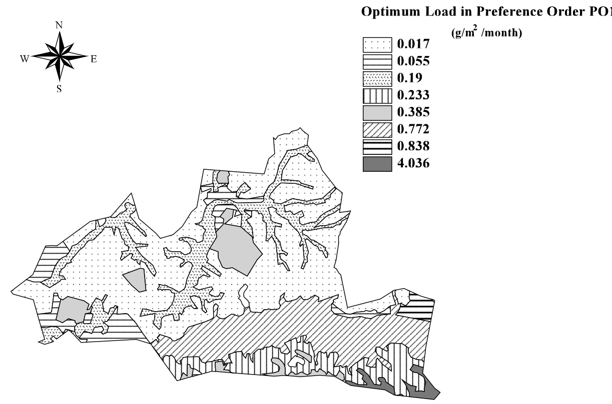

Fig. 7. Optimum allocated pollutant loads for preference orders PO1 with defined lower limits

Further, considering the fact that it is practically not possible to have LMU discharging zero level of pollutant load, optimization is also carried out by defining a minimum lower limit value of discharged pollutant load in (6)-(9). The values of lower limit, $L^l_{p_i}$, $L^l_{d_i}$, $L^l_{f_i}$, and $L^l_{c_i}$, are given on the basis of values of unit loading factors, as discussed above, and are taken as 0.19 g/m^2/month (paddy fields), 0.385 g/m^2/month (dry fields), 0.017 g/m^2/month (forests) and 0.055 g/m^2/month (cities), respectively. Therefore, the constraints in (6)-(9) in this case become:

$$L_{p_i} \geq 0.19 \qquad i = 1, 2, \ldots, I_p \qquad (10)$$

$$L_{d_i} \geq 0.385 \qquad i = 1, 2, \ldots, I_d \qquad (11)$$

$$L_{f_i} \geq 0.017 \qquad i = 1, 2, \ldots, I_f \qquad (12)$$

$$L_{c_i} \geq 0.055 \qquad i = 1, 2, \ldots, I_c \qquad (13)$$

The linear programming problem is solved again using the lower limit constraints (10)-(13). The optimum solutions for this case, for both of the preference orders PO1 and PO2, are shown in Figs. 7 and 8. In this case also preference orders PO1 and PO2 are same as defined earlier. For both preference orders PO1 and PO2, all the LMUs (except LMUs p_3, f_5, c_5, and d_8) get the same optimum discharged pollutant load as its defined lower limit value (Figs. 7 and 8). In this case, for PO1, optimum discharged pollutant loads for LMUs p_3, f_5, c_5, and d_8 are 0.772, 0.233, 0.838 and 4.036 g/m^2/month, respectively (Fig. 7), and for PO2 the corresponding optimum discharged pollutant loads are 0.688, 0.203, 3.139 and 3.504 g/m^2/month, respectively (Fig. 8). Total discharged pollutant load from all LMUs for PO1 is 1,827,817 g/month and that for PO2 is 1,836,028 g/month, for this case. The shown preference orders are just an example. The decisions-makers can have choice of preference orders based on the need of water resources users. The different combination of preference order can be obtained by changing the values of α, β, and γ.

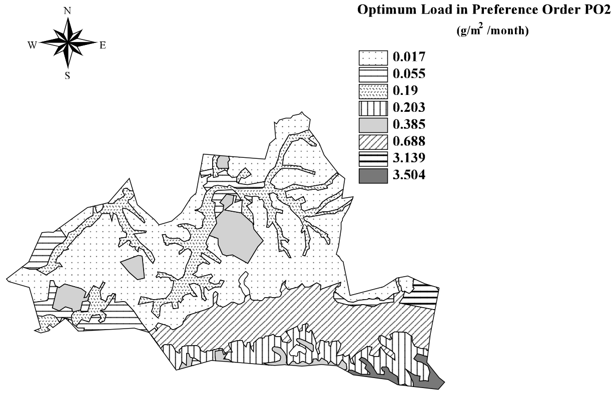

Fig. 8. Optimum allocated pollutant loads for preference orders PO2 with defined lower limits

IV. Conclusion

The model for allocation of optimum discharged pollutant loads from non-point sources, by maximizing allowable total loads, is developed in this study. The use of ArcView GIS is incorporated to model the study area and to compute the flow length and area of the LMU. The formulated method is demonstrated in a sub-watershed of the Yasu river basin, Shiga prefecture, Japan. The values of optimum discharged pollutant load from different LMUs are observed to be sensitive to preference order of type of LMUs. The model can be used for allocating optimum discharged pollutant loads from LMUs in a drainage basin based on preference order of decision maker's choice. Further studies will be required to estimate a more appropriate value of self-purification coefficient, λ, to generate more reliable solutions.

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