MATHEMATICAL PRIORITIZATION OF WASTE WATER TREATMENT INVESTMENT IN COLOMBIA

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ABSTRACT

Colombia, like most countries in the third world, has lacked an adequate planning process for the design, construction, and operation of wastewater treatment facilities in most municipalities. National, regional and local agencies have conflicting criteria for managing this sector. Furthermore, there is a lack of adequate tools to support decisions with appropriate environmental, financial, social, and technical information. In this paper, a computer model is presented as a tool to support the decision making process for planning municipal wastewater treatment facilities in Colombia at a national level. A geographical information system was used to obtain a structured river network from a digital elevation model. Modeling dissolved oxygen, biochemical oxygen demand, and coliform bacteria throughout the entire national drainage network allowed the analysis of several wastewater treatment scenarios, using bacteriologic contamination (*e.g*. coliform bacteria) as the main indicator of public health risks resulting from wastewater pollution. Using multivariate analysis, different wastewater

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treatment scenarios were analyzed to determine their effectiveness to mitigate wastewater pollution, based on environmental, socioeconomic, and infrastructure criteria. As a result, prioritizations for investment in wastewater treatment plants were obtained at municipal and basin levels. The decision making tool integrates the objectives of the national agencies involved in wastewater management policies, solving the conflicts between agencies and optimizing the use of financial resources for the wastewater sector.

Key words: water quality modelling, wastewater investment prioritization, multicriteria prioritization

INTRODUCTION

Planning investments in wastewater treatment facilities in Colombia has been done without unified objectives between involved governmental agencies, and in many cases decisions have been made without appropriate information. The lack of a unified position of the governmental authorities has been the result of a lack of unified national objectives regarding wastewater pollution problems, duplicity of agencies functions, and lack of defined roles and responsibilities of each agency. At the national level, three Ministries are involved in the decision making process for the construction and operation of wastewater treatment facilities: the Ministry of the Environment[2], the Ministry of Economic Development (MED)[3], which in 2001 defined the 389 municipalities (among a total of 1068) with higher priority for

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[2] Responsible at the national level of the pollution control, environmental quality, and natural resources management. Recently restructured as the Ministry of Environment, Housing, and Territorial Development (MEHTD), it assumed responsibilities on wastewater treatment facilities that previously were assigned to the MED.

[3] Mainly in the administration of the financial resources for their construction. Currently some of these responsibilities were translated to the MEHTD.

investment in wastewater treatment facilities, based only on economic and public infrastructure criteria, and the Ministry of Public Health (MPH)[4]. Another governmental agency at the national level, the National Planning Department, has also been involved in the decision making process. Conflicting interests and needs also appear at the regional and local level, i.e., the Regional Environmental Authorities (CARs)[5], the Public Domestic Service Superintendence (SSPD)[6], and the municipalities. As a result several wastewater treatment facilities have been built, without considering appropriate environmental indicators in the decision making process.

Between 2001 and 2002, Uniandes (2002) developed for the Ministry of the Environment a study for the Decennial Wastewater Management Plan, whose primary objective was to establish the priorities in investment needs for municipal wastewater treatment infrastructure for the period 2001 - 2011. For this purpose, a water quality model was developed to determine the impact of domestic wastewater discharges on the national river network. Modelling of dissolved oxygen (DO), biochemical oxygen demand (BOD), and total coliforms was carried out using a simple Streeter-Phelps formulation including the anaerobic component. Demographic projections were considered to calculate wastewater discharges and contaminant loads. In addition, surface stream flows were estimated for a mean dry weather flow condition. Coliform bacteria modelling received special attention because its results,

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[4] Before the creation of the Ministry of the Environment in 1993, it issued several environmental regulations, including water quality and wastewater standards.

[5] The CARs are the maximum environmental authorities at the regional level. They must follow the national environmental policies and plans issued by the MEHTD.

[6] The SSPD monitors and controls the performance of public service companies, owned by both the private and the governmental sectors.

compared to the water quality standards of the Ministry of Public Health (1984) allowed the definition of critical reaches on the river network. The results of the water quality model were used as input for a multicriteria analysis model. The latter model supported he prioritization process for investment in wastewater treatment facilities at a regional scale. This model uses existing statistical information available for each municipality in the country.

WATER QUALITY MODELING

Due to the lack of an entire structured digital river network for the country, a synthetic river network was generated from a 1:750,000 Digital Elevation Model (DEM). Using *ArcView 3.2*, a base map of 5417 rows and 3976 columns with a pixel size of 342 meters was generated. *RiverTools 2.4* was then used to produce a structured synthetic river network, based on a drainage pathway map for every pixel and a vectorized flow network. The flow network had 80,402 reaches, with attributes like coordinates for the upstream and downstream nodes of each reach, Strahler orders, downstream accumulated drainage area and slope.

The hydrologic scenario for the water quality simulation on the river network was taken from Vélez *et al* (2000) based on a long term annual water balance, i.e. precipitation – real evapotranspiration, disaggregated into monthly values using the model Global Monthly Reservoir – 2 Parameters (GR2M) model. February is a generalized dry weather month in Colombia. It was therefore chosen as a typical hydrologic scenario for the analyses. The corresponding stream flow yield map was integrated spatially over the catchment area in order to estimate stream flow discharges.

Data of municipal population was obtained from the national statistics agency (DANE) and processed according to the Colombian Water Supply and Sanitation Code (RAS, 2000) to estimate, for each municipality, the population for year 2011. Also, a per capita BOD load was estimated according to the RAS recommended value of 50 grams per capita per day (g/capita-d). The per capita BOD load was corrected with reduction factors that take into account the chemical and biological transformations that can take place in the sewage system and in small streams, whose magnitude is a function of town size (values based on a study of Uniandes, 2001). Thus, for municipalities with less than 500,000 inhabitants the per capita a value of BOD load of 50 g/capita-d was used; between 500,000 and 1’000,000, 43 g/capita-d; between 1’000,000 and 3’000,000, 36 g/capita-d, and greater than 3’000,000, 30 g/capita-d.

The wastewater flows were calculated using return factors given by RAS (2000). Each wastewater discharge and its corresponding BOD_5 load were assigned to the nearest node of the river network.

Oxygen saturation concentration as a function of elevation was calculated using the expression developed by Gameson and Robertson (1955),

$$o_s = \frac{475}{T + 33.5} e^{-(Z/8631)} \qquad (1)$$

where

o_s = oxygen saturation concentration (mg/L)

Z = elevation above sea level (m),

T = average temperature (ºC) as a function of altitude.

Given the tropical location of Colombia, air temperature is mainly a function of Z. The expression used by the model is $T = 27.05 - 0.0057Z$, (Vélez *et al*, 2000), which was applied in each node of the digital river network. Stream flows for each reach of the river network were calculated by adding the wastewater flow to the cumulative stream flow up to the discharge sites. For modelling BOD and DO in the aerobic reaches of the network, the well-known simple Streeter-Phelps model was applied (*e.g.* Chapra, 1997):

$$L = L_0 e^{-k_d t} \quad (2)$$

$$o = o_s - \frac{k_d L_0}{k_r - k_d}\left[e^{-k_d t} - e^{-k_a t}\right] - (o_s - o_0)e^{-k_a t} \quad (3)$$

where L_0 = initial BOD_u concentration (mg/L)

L = final BOD_u concentration (mg/L)

o = DO concentration at the downstream end of each reach (mg/L)

o_s = saturation dissolved oxygen concentration (mg/L)

o_0 = initial DO concentration (mg/L)

k_d = organic matter decay rate (1/day), k_a = aeration rate (1/day)

t = travel time (day) computed using velocity and length data.

Anaerobic decay of organic matter in some reaches of the river network was represented using a linear model, proportional to the reaeration rate, i.e., $L = L_0 - k_a o_s$.

In order to determine flow velocity, an empirical equation was used (Harvey, 1997),

$$v = 0.094 + 0.0143 \cdot \left(\frac{A_T^{1.25} \cdot \sqrt{g}}{Q_a}\right)^{-0.919} \cdot \left(\frac{Q}{Q_a}\right)^{-0.469} \cdot S^{0.159} \cdot \frac{Q}{A_T} \quad (4)$$

where v = average velocity (m/s)

Q_a = long term mean discharge (m^3/s)

Q = stream flow of interest in summer or winter

S = longitudinal channel bed slope

A_T = upstream tributary area (m^2).

The channel depth h (m) was estimated using geomorphologic relationships (Leopold *et al*, 1964), and field data from several basins in Colombia. The resulting formulation is expressed in terms of Q and v as $h = (Q/7v)^{0.4}$. The reaeration coefficient (k_a) is calculated according to the general equation presented by Chapra (1997) as,

$$k_a = \alpha \frac{v^\beta}{h^\gamma} (1.0241)^{(T-20)} \tag{5}$$

where T = average temperature (ºC), and *a*, *ḅ*, and *g* are coefficients.

Depending on reach channel depth and velocity, the model uses the values of the parameters corresponding to Owens-Gibbs, O'Connor-Dobbins, or Churchill formulations. The decay coefficient for organic matter K_d was calculated using $K_d = 0.23(1.135)^{(T-20)}$ for temperatures below 20ºC, and $K_d = 0.23(1.056)^{(T-20)}$ otherwise.

The natural death of coliform bacteria was modeled using a first order decay rate equation, with a decay coefficient varying with temperature: $X = X_0 e^{-kt}$, where X = bacterial concentration at the each reach end, X_0 = initial bacterial concentration, t = travel time along the reach, and k = decay coefficient for the coliform population, calculated as a function of temperature T as $k = 1.5(1.08)^{(T-20)}$ (Chapra, 1997).

The water quality model results were used to generate maps representing the spatial distribution of coliform bacteria, BOD, and DO concentrations making use of appropriate color legends (see Figures 1 and 2, for DO and coliform bacteria). Heavy BOD pollution and oxygen depletion were found only after few municipalities, caused by high populations, low precipitations, higher temperatures, and mild slopes. Coliform concentrations were compared to water quality standards established for different water uses, according to the 1594/84 Decree of the MPH. Critical streams were defined as sections of the river network with bacterial concentration exceeding 20,000 microorganims/100mL, falling in the category of non treatable water. A critical watershed was defined as a group of municipalities which wastewater discharges cause concentrations higher than 20,000 coliform/100mL in downstream reaches where other municipalities are located. On the other hand, if the contaminating municipality does not generate critical conditions to municipalities downstream, the stream is considered an isolated case of contamination. Several treatment scenarios were run, beginning with Scenario 0, a baseline scenario with no wastewater treatment in year 2011; Scenario 1, corresponding to the 389 municipalities with higher priority defined by the MDE in 2001 (SIAS, 2001); Scenario 2, for the first ranked 389 municipalities using the objective multicriteria prioritization explained below; Scenario 3, for the first ranked 389 municipalities using environmental prioritization, and four more scenarios summarized in Table 1.

Fig. 2. Dissolved Oxygen Modelling

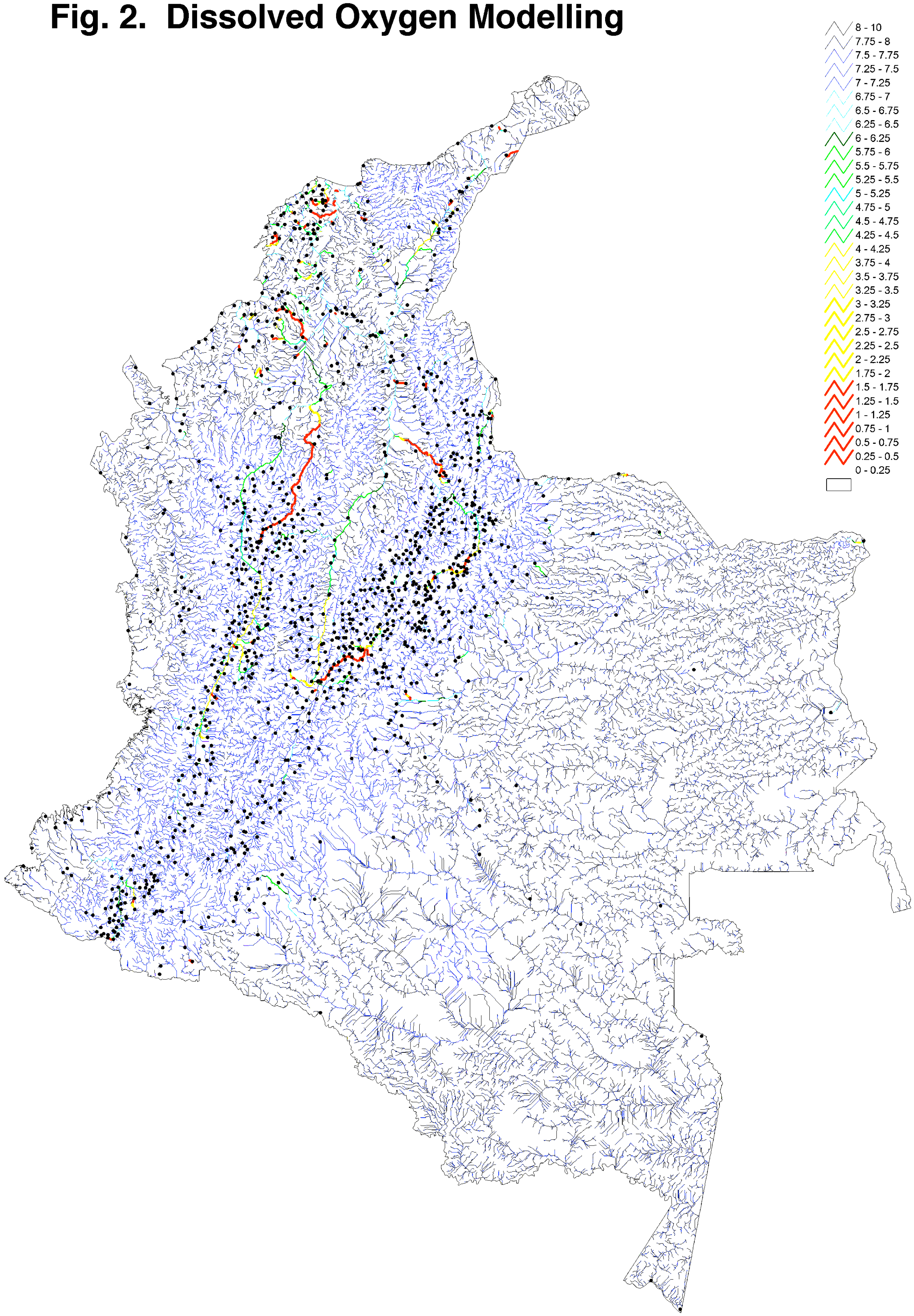
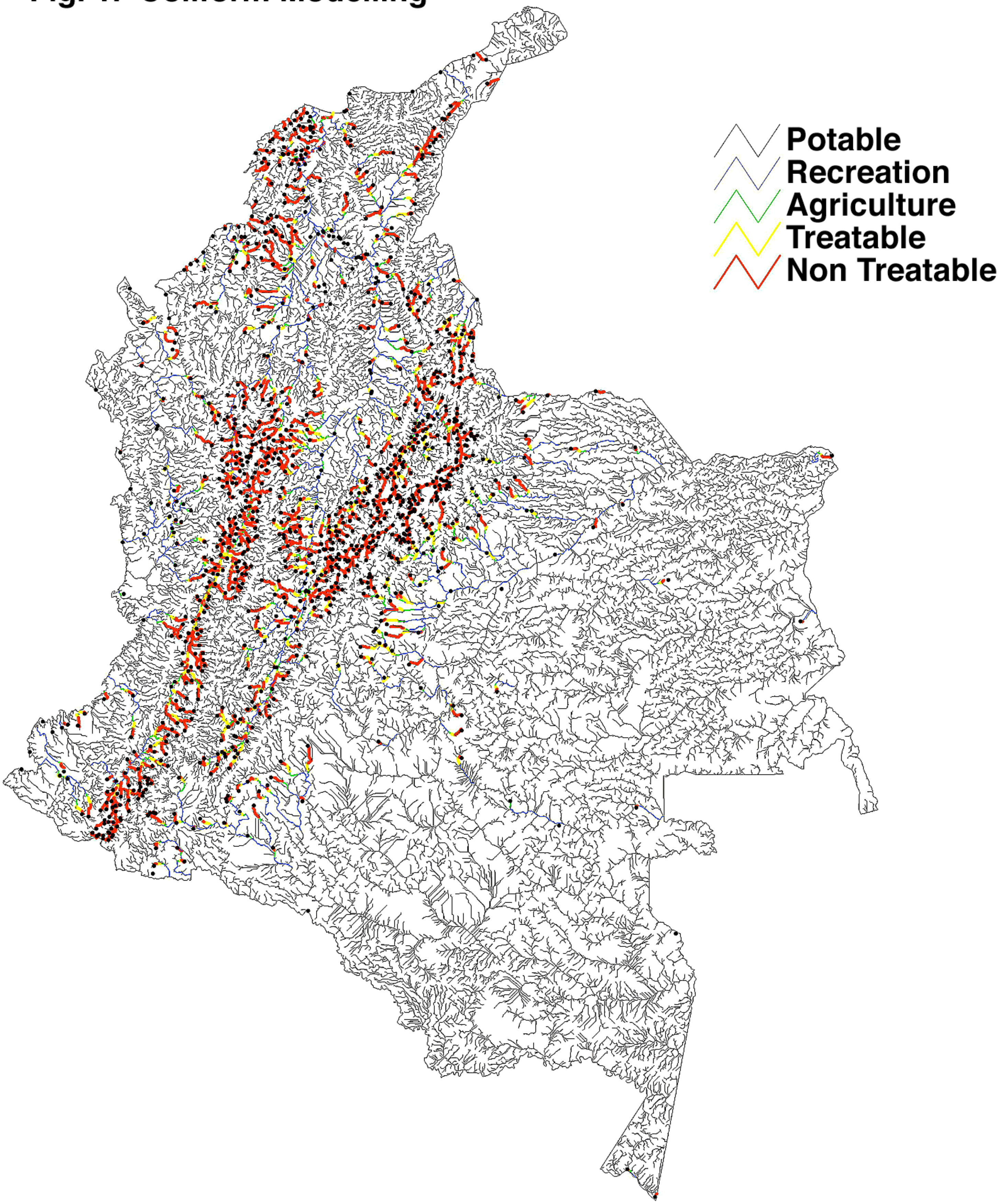


Fig. 1. Coliform Modelling



PRIORITIZATION

From the various available multiobjective methods (Smith *et al*, 2000), the Weighted Average method was used in this work. This method considers indifferent value functions for each objective, and uses a sum as an aggregation rule. Because the individual criteria may be valued under different scales, they must be normalized. Following the normalization, weighing factors are assigned by the planner to each criterion. The aggregated function is:

$$U(\mathbf{x}) = \sum_{j=1}^{p} w_j f\left[Z_j(\mathbf{x})\right] \qquad (6)$$

where p = number of criteri

w_j = weighting factor assigned to the jth criterion by the decision-maker

$Z_j(\mathbf{x})$ = value of the jth criterion calculated with n variables $\mathbf{x}$

f represents a non-linear function that varies between 0 and 1. For f a linear function or the cumulative beta density function was chosen. The latter varies from 0 to 1, it can be defined for any limited range [a, b], and it can be easily adjusted to different cumulative sample histograms (Uniandes, 2002). To select an alternative from a discrete set, the option with the highest relative value $U^* = \max\{U_1, U_2, ..., U_m\}$ is chosen, where m represents the number of alternatives being evaluated. The priority rank between different alternatives is established by ordering the U_i values from the largest to the least, resulting in the prioritization rank of alternatives.

Municipal prioritization was carried out based on the weighted average method. The first step was to define variables that use available information for the 1068 municipalities: a)

Municipal Fulfilled Basic Necessities Index, CNBI, b) Municipal Water Supply Coverage, ACU, c) Municipal Sewer System Coverage, ALC, d) Availability of Municipal Potable Water Treatment Plant, PTAP, e) Municipal Population, POB, f) Municipal Weighted Average Length, LONG, of critical reaches contaminated by the municipality with coliform concentration greater than 20,000/100mL, and g) Municipal Coliform Concentration, COLI, at the wastewater discharge site. These last two variables were obtained from the water quality model. For each variable, cumulative histograms were calculated to describe the sample data distributions, and appropriate linear or cumulative beta distributions were fitted. Given that these variables may present some degree of correlation, multivariate analyses were carried out to determine Pearson correlation coefficients, P statistic values, and principal components. These were used to obtain objective weighting factors for Ec. 6: CNBI, 19.74%; ACU, 6.14%; ALC, 13.78%; PTAP, 20.35%; POB, 16.7%; LONG, 11.49%, and COLI, 11.8%. If these variables are grouped in common areas such as Environmental and Public Health (EPH), Public Service Infrastructure (PSI), and Financial criteria (F), the corresponding weighting factor values are 34.3% for EPH, 34.5% for PSI, and 31.2% for F. Other weighting factors were subjectively defined in order to simulate different scenarios perceived as feasible by the decision makers. In general, the main municipalities for wastewater treatment prioritization are Bogotá, Medellín, Tunja and Manizales.

The same procedure used for the municipal prioritization was applied for watershed prioritization, where instead of analyzing individual municipalities, the assessment was developed for the 95 critical basins identified with the aid of the water quality model. In this case, the most critical watersheds are associated with the following urban areas: Bogotá, Medellín, Sogamoso, Bucaramanga, Manizales and Armenia.

Table 1 shows some results of the water quality and prioritization model for the treatment scenarios described above. For zero treatment the total length of reaches in critical watersheds is 6,214 km, whereas treatment in the first ranked 389 municipalities using balanced EPH, PSI and F criteria (multicriteria prioritization) reduces to 2,553 km (reduction of 595 km). The critical length reduces further to 2,348 km when the sole EPH criterion is applied. These values are smaller than those resulting from de 2001 MED's prioritization. There are 146 coincident municipalities when the MED's prioritization and the first ranked 389 municipalities using environmental prioritization are compared, and 252 common municipalities in MED's prioritization with respect to the first ranked 389 municipalities using balanced EPH, PSI and F criteria.

Table 1. Results of Modelling Scenarios

Scenario	Critical Watersheds			Isolated Stream	Total
	Total Length (km)	Reduction % with respect to Zero Treatment	Average Reduction of Critical Length per Municipality (km/Mun)	Total Length (km)	Total Length (km)
(0) Zero Treatment	6,214	0	0.0	4,938	11,152
(1) 389 MED	3,601	42	6.7	4,068	7,676
(2) First ranked 389 Multicriteria	2,553	59	9.4	4,351	6,914
(3) First ranked 389 Environmental	2,348	62	9.9	4,041	6,400
(4) 146 Coincident MED-Environmental	4,572	26	11.2	4,876	9,459
(5) First ranked 146 Environmental	4,145	33	14.2	5,443	9,603
(6) 252 Coincident MED-Multicriteria	4,031	35	8.7	4,549	8,589
(7) First ranked 252 Multicriteria	3,510	44	10.7	4,925	8,445

CONCLUSIONS

Numerical models may help to increase environmental benefits, and protect public health when used as planning tools to assist the decision-making process. This study is the first effort in Colombia to create a water quality model for the whole country's river network.

The study focused on treatment scenarios that are most efficient regarding the reduction of public health risks. From this perspective, the most effective prioritization of municipalities is obtained when only environmental criteria (*i.e.*: coliform concentration, weighted average critical length, and population) are used. Investments dealing with public health require secondary wastewater treatment and also disinfection.

This modelling and prioritization exercise not only guarantees a reduction of health risks, but also leads to a more efficient investment of public resources. Comparing Scenario 7 (first ranked 252 municipalities using multicriteria prioritization) versus Scenario 1 (389 municipalities with higher priority according to the MDE), nearly the same reduction of contaminated length is obtained. By investing in the former a reduction of contaminated length of 44% is obtained versus 42% if investment is carried on in the latter 389 towns. This would mean that Colombia would not have to construct 137 additional plants to achieve similar environmental quality. A similar situation occurs with Scenario 5 (first ranked 146 municipalities using environmental prioritization) and Scenario 6 (252 coincident municipalities using multicriteria prioritization and MDE's prioritization).

In 2001, the Ministry of Economic Development defined a list of 389 priority towns to invest in the construction of wastewater treatment plants, based on economic and public infrastructure criteria. This list was compared with the first ranked 389 municipalities using environmental prioritization, finding 146 coincident municipalities. The same procedure was done with the multicriteria prioritization, and the outcome of coincident municipalities was 252. From the wastewater management point of view, there should be no question about investing in the 146 coincident municipalities, because they comply with the objectives of the Ministry of the Environment and the Ministry of Economic Development, while reducing efficiently the contaminated length of the river network.

Using microbiological water quality as a pollution indicator allowed the unification of investment eligibility criteria for wastewater treatment infrastructure from the MEHTD and the MPH, governmental agencies responsible for managing water quality at the national level.

BIBLIOGRAPHY

Chapra, S.C., (1997), Surface Water Quality Modeling. The McGraw-Hill Companies, Inc. New York.

Fair, G.M., J.C. Geye,r and D.A. Okun, (1971), Elements of Water Supply and Wastewater Disposal. John Wiley ,and Sons, Inc. New York.

Gameson, A.L.H., and K.G. Robertson. (1955). “The Solubility of Oxygen in Pure Water and Sea Water”, *J. Appl. Chem*, vol. 5, p. 502.

Leopold, L.B., M.G. Wolman and J.P. Miller. (1964). “Fluvial Processes in Geomorphology” Freeman, San Francisco.

RAS - Reglamento del Sector de Agua Potable y Saneamiento Básico. (2000). Ministerio de Desarrollo Económico, (in spanish).

SIAS. (2001).“Aguas Residuales” – Documento y bases de datos digitales. Ministerio de Desarrollo Económico, (in spanish).

Smith, R., O. Mesa, I. Dyner, P. Jaramillo, G. Poveda y D. Valencia, (2000), "Decisiones con Múltiples Objetivos e Incertidumbre", Postgrado en Aprovechamiento de Recursos Hidráulicos, Facultad de Minas, Universidad Nacional de Colombia, sede Medellín, Segunda Edición, (in spanish).

Uniandes, (2001). Departamento de Ingeniería Civil y Ambiental. Modelación de la Calidad del Agua del Río Bogotá – EAAB. Bogotá D.C., (in spanish).

Uniandes, (2002), Departamento de Ingeniería Civil y Ambiental. Aplicación de un Modelo Numérico para la Priorización de la Gestión de Aguas Residuales Domésticas en Colombia. Bogotá D.C., (in spanish).

Vélez, J., G. Poveda and O. Mesa, (2000), "Balances Hidrológicos de Colombia", Universidad Nacional de Colombia, sede Medellín, Colciencias, Unidad de Planeación Minero-energética, UPME, Medellín, (in spanish).