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A Methodology for Water Quality Assessment in Developing Regions: A Case Study of China's Yellow River

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Abstract

Due to limited data and scarce financial resources in developing regions, policy decisions for managing water resources must often be made without a full understanding of what potential impacts on water quality may result. This study demonstrates a methodology for utilizing georeferenced statistical data to assess the primary pollution contributions and to model the physical impacts resulting from these contributions. Using socio-economic data on population, agricultural production and industrial output provides a basis for evaluating the potential effects on the current water quality situation and allows a method to assess the influences resulting from changes of these socio-economic patterns. This study focused on evaluating the current conditions in the Yellow River in China. A conceptual model is developed to estimate Biochemical Oxygen Demand (BOD) generation and link these sources with the hydrologic characteristics of the landscape to generate BOD loadings into the main river channel. In-stream fate and transport modeling is then used to estimate the BOD and dissolved oxygen concentrations throughout the river.

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About the Author

Kevin Wheeler is a graduate (M.S) of the University of Colorado, U.S.A. This work represents the first three months of research towards his Master's thesis conducted during the Young Scientists Summer Program 1999. He completed his master's degree in May 2000 in Environmental/Water Resources Engineering.

This work earned him the Mikhalevich Scholarship award that allowed him to return to IIASA and continue developing the model described in this paper. He is also currently associated with the Center for Advanced Decision Support for Water and Environment Systems in Boulder, Colorado and the Long Term Ecological Research station project in Antarctica.

A Methodology for Rapid Water Quality Assessment in Developing Regions:
A Case Study of China's Yellow River

Kevin Wheeler

Introduction

The necessity of sufficient and good-quality water often acts as a limiting factor to the viable development of a region. Differing uses for water require various levels of water quality. Hence, the usefulness of water can vary significantly depending upon several physical and chemical characteristics. Furthermore, environmental health from both an ecological and anthropocentric viewpoint depends greatly upon the quality of the water resources. Both the basic availability of clean drinking water and access to proper disposal facilities for human waste have a direct effect on the health of a community. The ability for an environment to degrade human waste is governed by the natural processes and methods used to manage or utilize waste products. Often, the disposal practices in developing countries have a direct impact on the water resources that downstream communities depend upon for consumption.

The generation and evaluation of water management policies in developing regions must often be done with little or no data on the actual quality of the water resources. This study outlines a methodology in which statistical census information can be utilized to predict socio-economic influences upon water quality. This type of study is useful because current water stress analyses generally assume that all water is usable by all sectors of society. Without the availability of more detailed data, a study of this type provides a method of characterizing this concept of 'useful' water versus water that is available but potentially unusable by certain sectors. This study attempts to determine what regions may be constrained by the level of contamination that a community is subjected to. The purpose of developing the methodology proposed in this study is to indicate the sensitivity of water quality due to population, agricultural, and industrial pressures. A study of this type should be seen as a tool for indicating areas that require a more extensive and exhaustive study.

Scales of assessment must be chosen to be both finite enough to include the major influences that affect water quality, yet extensive enough to examine impacts of policy decisions upon a system as a whole. Limitation of an analysis to a single large river system and its contributing basin area creates a significantly closed system that is only effected by the processes that occur within the basin area. Determination of the extent that water quality influences development requires that predictions of the chemical properties of the water resources be made throughout this area of interest. This modeling process is obviously a task that incurs several uncertainties without the direct access to parameters that are typically measured in water quality studies.

The water quality parameter of interest in this study is dissolved oxygen. This basic parameter is an overall indicator of an aquatic system's health. The presence of dissolved oxygen generally permits aerobic degradation of organic matter and thus defines a processing capacity of organic pollution. The introduction of organic matter into a river system has two major impacts. First, the presence of dissolved and particulate matter increases the turbidity of the water which can have effects such as influencing its usage as a domestic water supply and increase the difficulty of transport treatment and treatment. This increase of turbidity also inhibits plant growth and therefore hinders the production of oxygen. Furthermore, this increase in solids from organic pollution sources can create beds of sludge that emit noxious odors. The second effect of organic matter in river systems is the dramatic increase of heterotrophic organisms. Aside from the multi-trophic effects of this shift within the aquatic ecosystem structure, these organisms feed upon the organic matter in the river and concurrently consume oxygen.

Study Area

The methodology developed in this study was implemented on the Huang He (Yellow River) river basin in China. This region was selected for study due to the extreme variations in topography, climate and the potential for rapid land-use changes throughout the immediate future. In addition, the progress of China as a growing industrialized nation is certain to affect the world community as a whole.

Figure 1

The Yellow River is the second longest river in China (Figure 2). The headwaters begin in the Central Western region of the Yagradagze Mountains and flows eastwards making a turn to the north near the City of Langzhou. The river flows north for approximately 1000 kilometers and then turns eastward in the Inner Mongolia Province. After passing the city of Baotou the Yellow River bends southward and travels again for approximately 1000 kilometers to form the border of the Shangxi and Shaanxi provinces. At the confluence with the Wei He River, the Yellow River makes another sharp turn to the east and flows past the city of Zhengzhou in the Henan Province before turning northeast and flowing through the Shandong Province into the Bo Hai Sea.

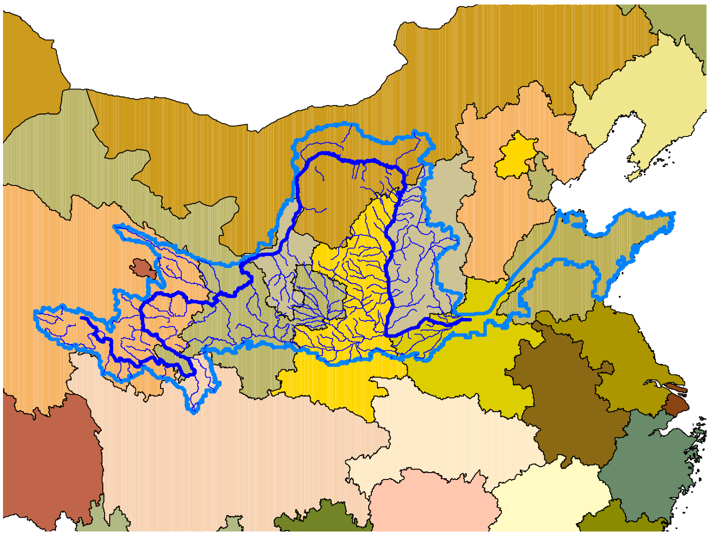

Figure 2

The total length of the Yellow River is 5,464 kilometers, which drains an area of approximately 745,000 sq. km. The waters of this river are estimated to be accessible by or be affected by 86 million people as of 1995. This study limits the area of interest to approximately 4000 kilometers reaching from the headwaters to the city of Zhengzhou. The reaches downstream of the study area are complicated with a riverbed artificially elevated by levees constructed during the past three millennia.

Methodology

The process of predicting water quality parameters for the Yellow River consisted of several steps and is the main focus of this study. The primary indicating characteristic for water quality measurement was chosen as dissolved oxygen. Dissolved oxygen is depleted by the presence of organic material due to heterotrophic decomposition. The traditional method of evaluating and modeling the relationship between organic matter and dissolved oxygen concentration is through the conglomeration of all organic matter into a single quantity of pollutant termed Biochemical Oxygen Demand (BOD).

Determination of Pollution Generation

The methodology used to determine pollution generation in the Yellow River Basin followed the Rapid Assessment procedure published by the World Health Organization (WHO 1982). This rapid assessment procedure is an across-the-board inventory of pollution generation based upon activities within the study area. Furthermore, this rapid assessment procedure is specifically intended for developing countries. The justification of such an assessment lies in the fact that although their may often be a good understanding of the general principals and practices of environmental health and pollution control programs, there is often a lack of specific data, especially in developing regions.

The basis behind rapid assessments lies in the assumption that statistical information on waste generators is directly proportional to waste generation quantities. These statistics may include information on population, agricultural production and industrial production. The determination of potential sources of pollution consists of a search for the most finite resolution statistical data. For the case of China, this data comes in the form of county-level statistics derived from Provincial Economic Yearbooks. Population data was acquired from IIASA Land Use Change Project. Agricultural statistics and industrial production data was made available via World Wide Web and funded by the Consortium for International Earth Science Information Network (CIESIN).

After acquisition of the county-level data, a spatial topology via geographic information system (GIS) was established by linkage of administrative (county) codes to existing polygon Arc/INFO coverages from IIASA. The extensive database supplied by CIESIN was examined to determine what census information could indicate significant contributing sources of pollution according to the rapid assessment procedure description (WHO 1982). Within the CIESIN database, there existed several 'No Data' values for many of the county-level data entries. Therefore the input sources were limited by the availability of information. For agricultural production, a decent coverage of Yellow Basin counties reporting year-end-stock of hogs and sheep was found (94% and 91% respectively). The data on the year-end-stock of cattle included only 38% of the counties within the Yellow River. These data sources were still used to achieve the best estimations possible. Slaughter of large animals was only recorded in the database for 22% to 30% of the counties, but again was included due to a lack of alternatives. Statistics of milk production and wool production were available for 36% and 58% of the Yellow Basin counties respectively. Unfortunately the incompleteness of this CIESIN database is a reality that must be accepted until further data can be acquired.

The actual procedure for calculating waste production includes using the statistical census data (e.g. number of people, head count of pigs, tons of wool produced, etc.) and multiplying this information by an appropriate pollution factor or waste factor. Pollution factors and waste factors were supplied by the Rapid Assessment procedure manual (WHO 1982) and defined as follows:

Pollution Factor is the amount of a pollutant or a combination of pollutants released into the environment by an industry (directly, or indirectly through municipal sewers or through the municipal waste collection and treatment network) per unit of merchandise produced or per unit of raw material consumed, depending on the type of industry or method of calculation of the pollution factor.

Waste Factor is the total amount of waste released into the environment (directly, or indirectly through municipal sewers or through the municipal waste collection and treatment network) by one person per year in a given area.

Proper unit conversions are often necessary to multiply the statistical information by the pollution/waste factors. For example, determination of the quantity of BOD released into the environment from slaughterhouse production required introduction of further assumptions. The statistical data for China described the head count of each type of animal slaughtered while the appropriate pollution factor was in kilograms of BOD produced per metric tons of live weight killed (LWK) per year. It was then necessary to assume an average weight of the animals slaughtered. The weights used were:

Average cattle weight = 430 kg

Average hog weight = 120 kg

Average sheep weight = 43 kg

An example calculation of yearly BOD generation would be as follows:

$$5000 Hogs Slaughtered \times \frac{120 kg}{Hog} \times \frac{1 Ton}{1000 kg} \times \frac{6.4 kg BOD}{Ton LWK} = 3840 kg BOD \tag{1}$$

Similar calculations were done for

- Domestic Waste Generation
- Domestic BOD Generation
- Rural Waste Generation
- Rural BOD Generation
- BOD Produced from Cattle and Buffalo
- BOD Produced from Sheep and Goats
- BOD Produced from Slaughtered Beef Cattle
- BOD Produced from Slaughtered Fatting Hogs
- BOD Produced from Slaughtered Mutton Sheep
- BOD Produced from Milk Production
- BOD Produced from Sheep and Goat Wool Production

The waste generation units were volume produced per time while the BOD generation units were mass produced per unit time.

Determination of Waste Loading and River Flows

To apply this generation information as pollution inputs to the Yellow River, the entire river basin was subdivided into 131 sub-basins. The sub-basin boundaries were determined from a Digital Elevation Model (DEM) with a 5 kilometer resolution being processed with-in an Arc/INFO GRID function. The output of this sub-basin delineation was overlaid with a detailed river coverage. This overlay allowed for manual combination and editing of the output from the automatic sub-basin delineation. This sub-basin delineation also allowed the flow path to be divided into 131 reaches. This division was used for several reasons. First, dividing the river into distinct reaches allows estimation of flow contributions locations to the river. Each sub-basin was used as input to the CHARM runoff model. This hydrologic model uses several data sources such as temperature, precipitation, soil type, humidity, etc. to model the average monthly runoff from each sub-basin. This runoff value could then be divided into flow entering the river at a point and flow entering the river as a distributed source. The quantity of flow allocated to distributed sources corresponded to the amount of rural waste volume generated within each area. Another use for dividing the river into reaches is to allow for varying geometry along the river course. The changing geometry of the river could be estimated and entered into the model at these increments in terms of width and average depth. Due to a simple lack of detailed geometric information to integrate a hydraulic model, the source of the geometry data in developing regions is often limited to photographs and information gathered from individuals familiar with the region. With the lack of accurate channel cross-section data, these estimations are mandatory.

Specific to the Yellow River, a need to include 23 sub-sub-basins arose from the large Wei He tributary covering a large portion of the greater Yellow River Basin. This also allowed a separate model to be developed for this tributary and its output was used for input into the Yellow River model.

To determine which counties influenced which sections of the Yellow River, the initial approach was to assign each county to the sub-basin in which the majority of the area resided. This assignment scheme did create significant difficulty by causing variable sources of error depending upon the relative sizes of the sub-basins and counties. If the sub-basin encapsulated the vast majority of the county, the assumption would produce a valid assignment. However, if the county spanned several sub-basins, which was a frequent case in the upstream mountainous regions of the Yellow River, the pollution generated from the entire county would be assumed to flow from only one sub-basin. This assumption produced apparent large concentrated regions high BOD and low dissolved oxygen, when in reality the contribution would enter the river in a diffuse manner across several sub-basins. To improve this waste allocation process, county borders were overlaid with the sub-basin boundaries to create 2065 'basin-county' polygons. Almost half of these polygons were insignificant in size, yet kept for completeness. An assumption was made of uniform coverage of all pollution generating activities across each county. This was done to distribute each pollution source according to the physical percentage of area that each basin-county covered of the entire county. The basin-county polygons could then grouped according to the associated sub-basin. This procedure allows for the pollution-generating source to enter the river at the appropriate locations and distribute pollution generation from one county to multiple sub-basins if the county is relatively large. However, this grouping procedure does not incorporate the concept of routing the pollutants through the sub-basin.

The most simplifying assumption for pollution routing one can make is that all pollution-generating sources contribute entirely and equally to the river loading. The model was initially run under this assumption and can be interpreted as a 'worst case scenario' given the inputs are significantly complete. To introduce the concept of routing pollutants into the river, information concerning flow distance was necessary. A grid indicating the length of travel to reach the river allowed waste estimations to be reduced based on this distance.

Only in the simplest topographies or small enough scale can a basic distance to river derived independently from the land surface. Most realistic flow distances must be determined through digital elevation models. The process used to achieve this flow distance grid was through the use of the GIS WEASEL interface tool in development by the United States Geological Survey. This tools works interactively with Arc/INFO to analyze digital elevation models (DEM's). The GIS WEASEL inputs a DEM and calculates a flow direction grid based upon adjacent polygon elevation values. An initial flow accumulation field is determined and sinkholes and interior basins are detected. These sinkholes were filled to allow approximately proper drainage paths to be generated. From this sinkhole filled digital elevation model, a computational stream network was output. By varying the 'threshold' (precipitation/discharge equivalent) of the river basin, a more or less complex network of rivers can be generated. The threshold was adjusted until the computational river model closely matched the actual river path. However, the output stream network did not exactly match the reality of the river route, thus creating another source of potential error. An Arc/INFO grid was then generated that indicates the topographic flow length water must travel when falling upon a particular grid cell to reach the river channel. This grid was then overlaid with the polygons of basin-counties to determine the minimum, maximum and mean flow distance water must travel from the basin-county to the Yellow River. This information was then used to estimate the relative contributions that each basin-county polygon would have. Under the assumption that BOD decreases exponentially from the source as it travels toward the river, the following reduction equation was assumed:

$$InputBOD_{mass} = BODmass \times e^{(-Rf \times MeanFlowDist)} \qquad \textbf{(2)}$$

Input BODmass = Mass of BOD that enters the river (g/day)

BODmass = Mass of BOD Generated at the source (g/day)

Rf = Reduction factor (m^{-1})

MeanFlowDist = Average distance needed to travel to the river (m)

This crucial step allows for the reduction of waste entering the Yellow River from sources that are distant to the river itself. Waste generation in basin-counties could now reflect the effect of travel distance to the river. The reduction factors used are based upon the transport capability of each sub-basin. For example, dry arid regions would have a low tendency to transport organic matter and thus a high reduction factor. Steep areas with high surface runoff characteristics would transport organic matter more readily and thus have a lower reduction factor. The determination of reduction factors could be based on calibration. Unfortunately, the lack of actual water quality data for the Yellow River inhibits this calibration. Another approach would be to make estimates of reduction factors from other basins with similar topographic, soil and hydrologic properties. In this study a sensitivity analysis was done to see the effects of these reduction factors when applied uniformly across all sub-basins. The values of point BOD input, distributed BOD input and distributed waste volume input from each basin-county were summed for each sub-basin.

The resulting BOD loads into the rivers, in terms of mass per day, were then entered as input into in-stream dissolved oxygen model. The quantity of runoff coming from each sub-basin was divided into point inflow and distributed inflow. The quantity of distributed inflow was specified as the amount of distributed waste volume generated in the sub-basin. The point inflow was specified as the difference from the CHARM runoff output and the allocation to distributed flow.

Other factors that were used as input into the in-stream model included the dissolved oxygen of both the point source input and the distributed source input. These values were generally assumed to be at saturation for the point source inputs and 50% of saturation for the distributed source inputs. Each tributary that contributed a significant portion of the inflow could be modeled separately by this procedure to refine the input value of the dissolved oxygen concentrations. This was done for the large Wei He Basin due to its 40% contribution of downstream average inflow at the confluence with the Yellow River. This separate modeling of a tributary also gives a refined value for the BOD inputs into the Yellow River.

Temperature of the point and distributed inflows was also used as input into the in-stream model. These temperatures were derived from monthly grid data of China from the IIASA-LUC database. The sub-basins polygons were overlaid with the temperature grids and the average water temperature from in each sub-basin was specified as the average temperature of the sub-basin itself. This value could also be modified if the sub-basin is modeled separately, as was done for the Wei He tributary.

In-Stream Model

The decomposition of BOD is assumed to follow a first order decay with the presence of oxygen. Further assumptions that the BOD decomposition model assumes is the system remains at steady state and advection is the dominant transport mechanism in the river. Therefore the dispersion mechanism is neglected, limiting the applicability of the model to river systems upstream of tidal influences. Assuming complete lateral mixing along with this advection dominated system defines the river as a plug-flow reactor. The steady state assumption gives a valid representation given the limitation that monthly precipitation and temperature input data are frequently the most temporal resolute data available. Thus, the primary equation defining the concentration of BOD in a plug flow reactor under these assumptions is:

$$0 = -U\frac{dL}{dx} - k_r L \tag{3}$$

U = Stream Velocity (m/day)
L = Concentration of BOD (mg/L)
x = Downstream Distance (m)
k_r = Total Reaction Rate

The reaction rate is comprised of two parts

$$k_r = k_d + k_s \tag{4}$$

k_d = Decay Rate (day^{-1})
k_s = Settling Rate (day^{-1})

Two competing processes affect the oxygen concentration: The decay of the organic matter and reaeration by diffusion of oxygen from the atmosphere into the water. The reaeration process is governed by the difference between the actual dissolved oxygen concentration and the saturation concentration of oxygen. Thus the dissolved oxygen deficit is governed by the equation:

$$0 = -U\frac{dD}{dx} + k_d L - k_a D \tag{5}$$

D = Oxygen Deficit (mg/L)

D = Dissolved Oxygen Saturation Concentration – Dissolved Oxygen Concentration

k_a = Reaeration Rate (day_{-1})

The combination of equations (1) and (3) constitute the classic Streeter-Phelps point source model (Streeter and Phelps 1925) and produce a dissolved oxygen sag curve.

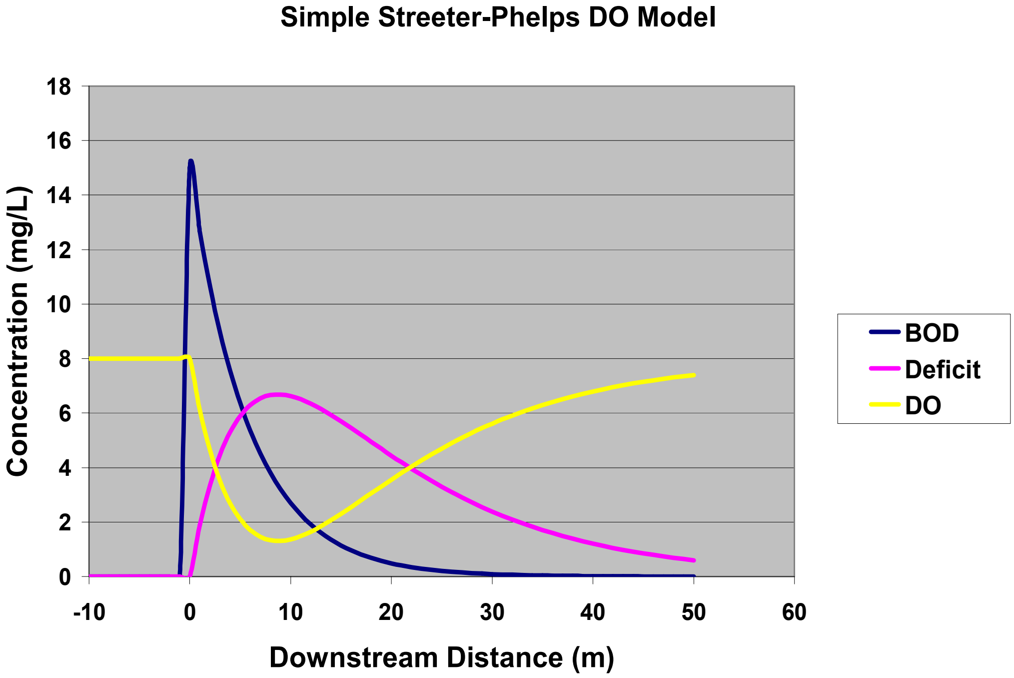

Figure 3

Reaeration rates have been shown to be dependent upon several factors. The depth of the channel and the velocity are the primary physical characteristics that influence oxygen transfer. O'Conner and Dobbins (1956) suggested the relationship:

$$k_a = 3.93\frac{U^{0.5}}{H^{1.5}} \tag{6}$$

U = Velocity (m/sec)
H = Mean Depth (m)

Churchhill et al. (1962) and Owens et al. (1964) described the relationship as:

$$k_a = 5.026\frac{U}{H^{1.67}} \tag{7}$$

$$k_a = 5.32\frac{U^{0..67}}{H^{1.85}} \tag{8}$$

respectively. The O'Connor-Dobbins formulas were used in this model due to the greater applicability for larger rivers, but any reaeration formula can easily be implemented. Surface features such as waterfalls and dams also contribute to changes in reaeration rates. However, due to the lack of information of such features, these changes are not included in the model. Furthermore, diurnal changes in oxygen concentration due to plant respiration and photosynthesis are beyond the scope of this analysis.

To accurately represent the possible scenarios, several modifications to the Streeter-Phelps model were implemented. The possibility of a river system becoming completely devoid of oxygen requires the decomposition process to be modified in such scenarios (Grundelach and Castillo 1970). In this case, the decomposition rate is limited by the rate at which oxygen passes the air-water interface. Therefore a zero order decay of BOD occurs as follows:

$$\frac{dL}{dt} = -k_a o_s \qquad \textbf{(9)}$$

o_s = Dissolved Oxygen Saturation Concentration (mg/L)

Note the right hand side of this equation remains constant under uniform and isothermal flow. This anaerobic condition persists until a sufficient amount of BOD has been removed and the reaeration mechanism dominates the decomposition process and dissolved oxygen concentrations can increase. This time is determined by the equation:

$$t_f = t_i + \frac{1}{k_d} \frac{k_d L_i - k_a o_s}{k_a o_s} \qquad \textbf{(10)}$$

t_f = Time at end of Anaerobic Condition
t_i = Start time of Anaerobic Condition
L_i = BOD at start of Anaerobic Condition

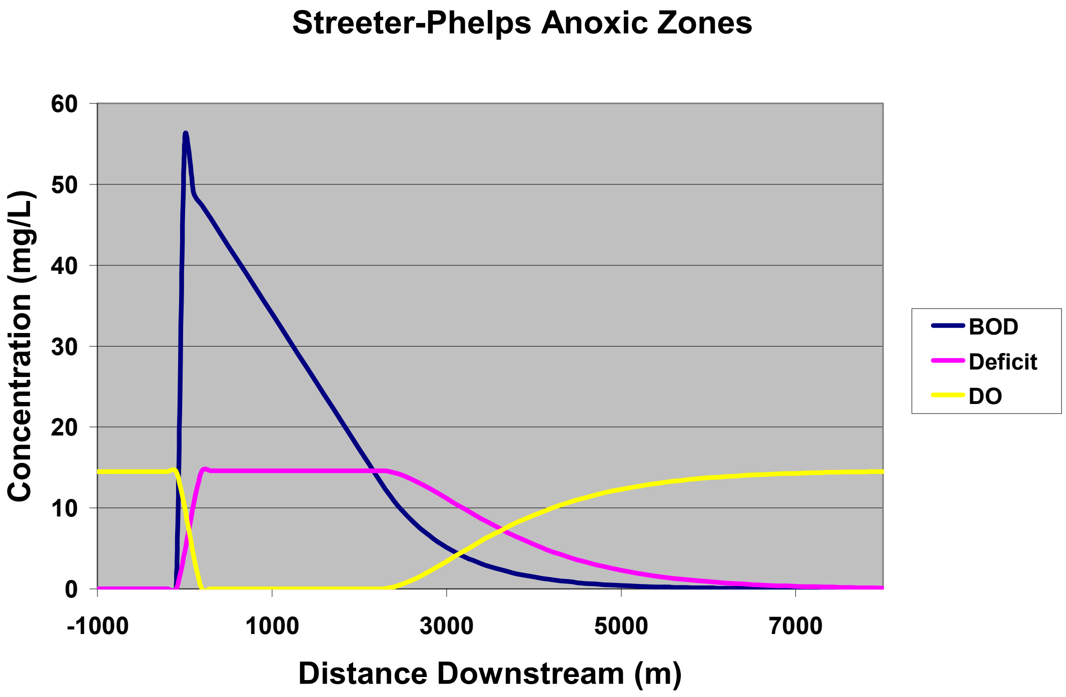

Figure 4

Figure 4 exhibits a point load that completely depletes the dissolved oxygen in the river and enters into an anoxic state.

Another necessary adjustment made to the basic Streeter-Phelps model was the introduction of distributed sources. Due to mainly agricultural sources, this pollution mechanism must be included to accurately model the distribution, transport, and fate of organic matter. Although various analytical solutions exist for introducing distributed sources, inclusion of flow with the source is easily managed by determining the quantity of distributed flow along with the corresponding BOD mass that is introduced over a reach of river and dividing it into finite elements. Each element can be introduced individually and equilibrium recalculated with the increased mass and flow. Equilibrium is calculated under the assumption that dissolved oxygen and BOD are conservative constituents. Another assumption is that density and heat capacity of water are relatively constant so a heat balance can be developed at each segment (Chapra 1997). With the constant recalculation of equilibrium, a distributed source can be represented by many point sources.

Results

The model was refined many times throughout the course of its development and is constantly undergoing development at the time of this report. The initial step of determining the BOD loadings into the Yellow River were as follows:

The BOD loading into the Yellow River was based upon the census information, which would indicate certain waste generation rates. With the available data provided by IIASA and CIESIN, the following total BOD sources within the Yellow River were determined:

	Number of Counties Reporting out of 289	**Percentage of Yellow River Counties Reporting**	**Amount**	**Unit**
Urban Population	289	100%	20,432,743	People
Rural Population	289	100%	65,623,867	People
Hogs	272	94%	15,382,900	Head
Sheep & Goats	280	97%	37,198,100	Head
Cattle & Buffalo	110	38%	2,732,542	Head
Hogs Slaughtered	93	32%	5,288,800	Head
Cattle Slaughtered	70	24%	417,146	Head
Sheep Slaughtered	76	26%	3,583,956	Head
Milk	103	36%	276,282.8	Metric ton
Sheep & Goat Wool	217	75%	34679	Metric ton

Table 1

The categories listed are as specified by the CIESIN database. The three categories ‘sheep’, ‘goats’, and ‘sheep and goats’ were combined by using the greatest value for each number to avoid double counting. This combination was also done for wool production. Incorporation of each waste factor/pollution factor and using the appropriate conversion factors resulted in total waste generation as follows:

	BOD Produced (tons/year)	**Percent of Point Generation**	**Percent of Total Generation**
Point BOD from Urban Population	414,282	95.92%	12.69%
Point BOD from Slaughter	8,545	1.98%	0.26%
Point BOD from Dairy	1,383	0.32%	0.04%
Point BOD from Wool	7,687	1.78%	0.24%
Total Point BOD	431,897		
	BOD Produced (tons/year)	**Percent of Distributed Generation**	**Percent of Total Generation**
Distributed BOD from Rural Population	455,635	16.08%	13.95%
Distributed BOD from Hogs	426,013	15.03%	13.04%
Distributed BOD from Sheep	1,295,363	45.71%	39.66%
Distributed BOD from Beef	657,001	23.18%	20.12%
Total Distributed Load	2,834,012		

Table 2

The initial scenario of assigning entire counties to one specific sub-basin resulted in regions of concentrated pollution in the upstream reaches of the Yellow River. Furthermore this initial scenario does did not include any reduction factors for the routing of pollutants through the sub-basins.

Dissolved Oxygen Distribution –Loads as Point Sources

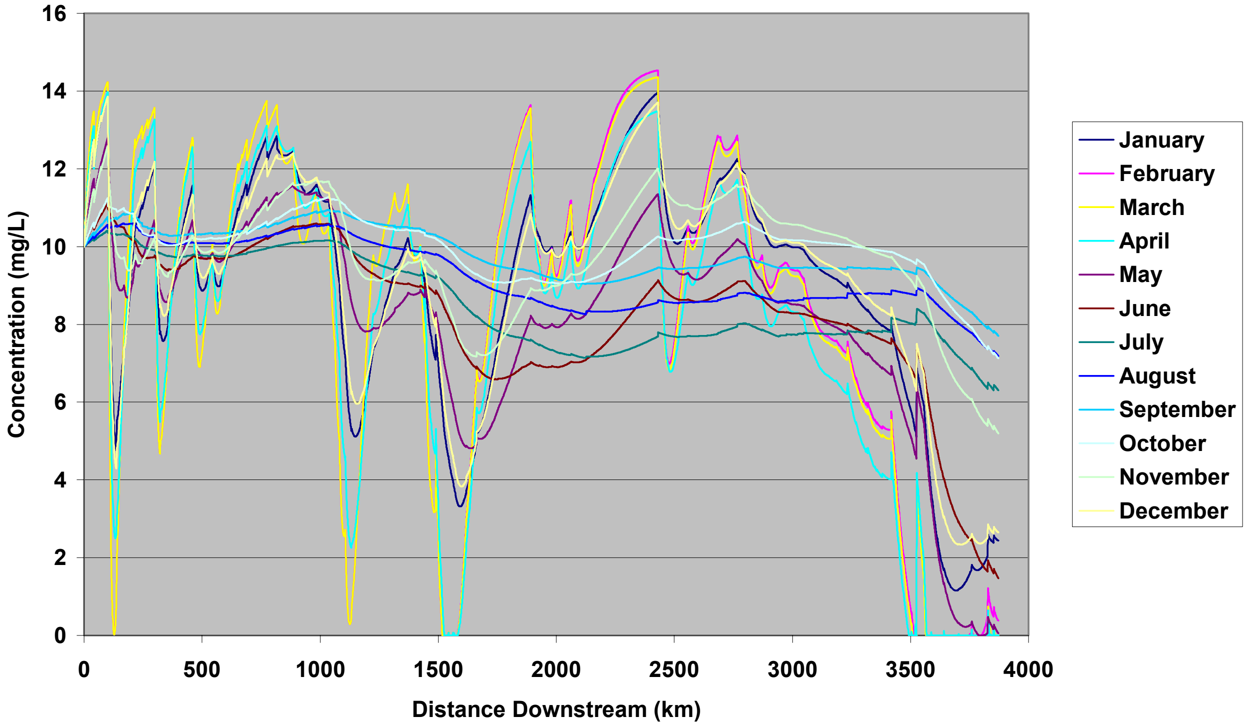

Figure 5

From this initial output, the seasonal variability of the dissolved oxygen concentration is apparent. The general pattern of erratic behavior through the end of winter to beginning of spring months and the relatively high and consistent concentrations of dissolved oxygen through the end of summer to beginning of fall months can be seen. The reason for this behavior is the eight-fold increase in flow the river is subjected to during the annual cycle modeled.

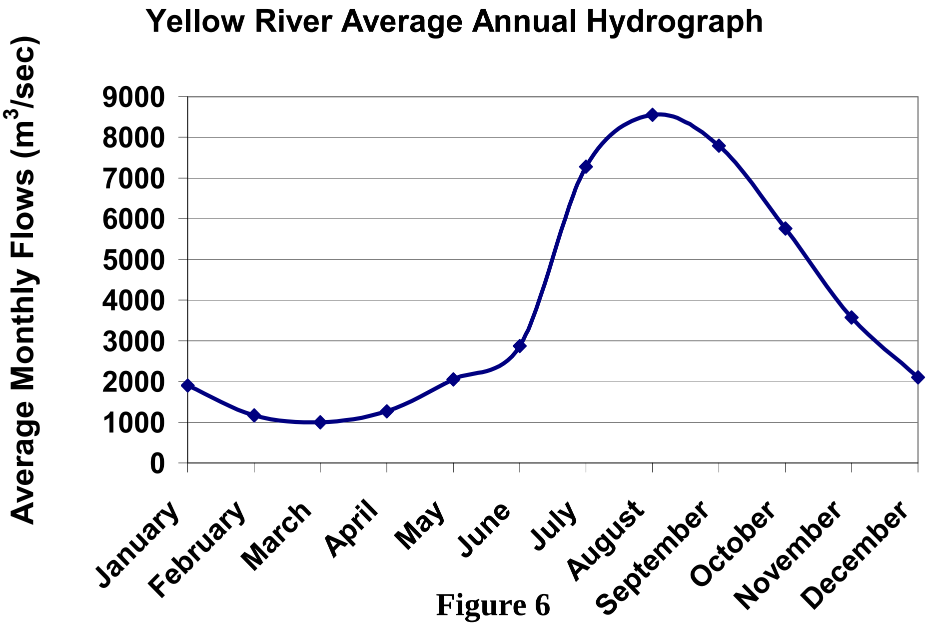

Figure 6

After modification of the model to include distributed sources and the reallocation of counties to sub-basins by the percentage area contained within each sub-basin, the modified dissolved oxygen distribution was modeled (**Figure 7**). This scenario still does not include the reduction factors or the correction introduced by separately modeling the Wei He tributary.

Dissolved Oxygen Distribution –
Loads as Point and Distributed Loads

Figure 7

Introduction of the independently modeled Wei He tributary allowed for a more accurate representation of the BOD concentration and dissolved oxygen of the inflow waters. The high effect of population residing in this sub-basin was apparent when examining the DO profile of the Wei He.

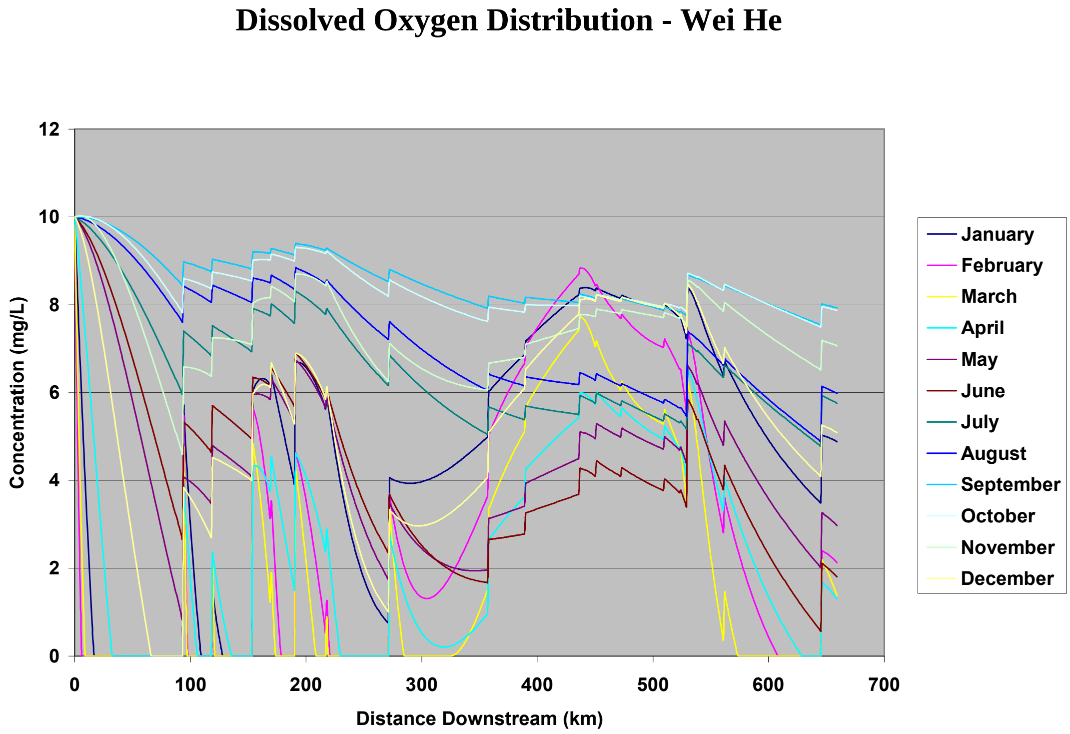

Figure 8

The outlet concentrations of the highly affected Wei He tributary were entered into the Yellow River Model to produce dissolved oxygen distributions and compare the effect of the independent modeling effort. Two extreme flow months are shown and only the affected portions of the river are shown for clarification.

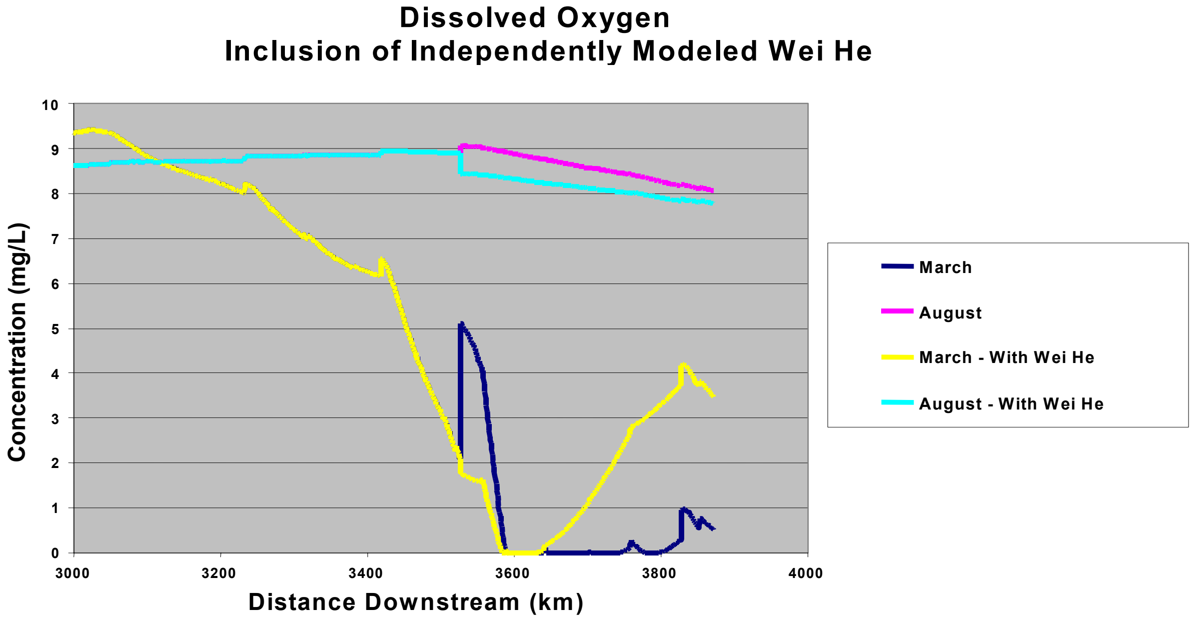

Figure 9

It is apparent that the most critical month according to the model output is March due to the lowest average monthly flow during this time period. Therefore, the following results will focus upon this month as a 'worst case scenario.'

The introduction of reduction factors due to the routing of BOD into the Yellow River was introduced. These reduction factors were applied to the total amount of point source BOD mass generated and the total amount of distributed source BOD mass generated. Without actual measurements of BOD and dissolved oxygen, a sensitivity analysis was done to observe the effects of this routing assumption. A wide range of reduction factors was introduced (0.000001 m^{-1} to 0.01 m^{-1}) to the entire basin and compared to the original case with no reduction factor.

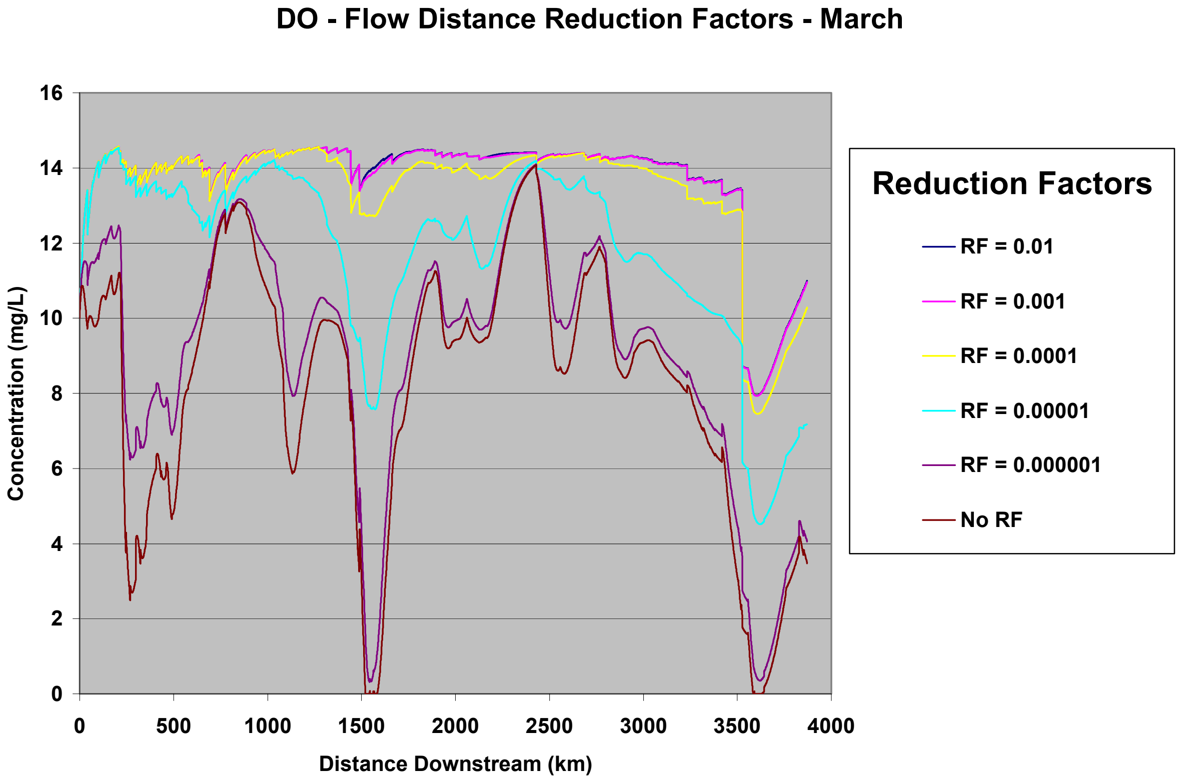

Figure 10

This reduction factor would ideally be individually specified for each sub-basin. This would be achieved through a calibration with actual water quality data if available, or would need to be assumed through studies of other basins with similar characteristics. Thus far no actual reduction factors for the Yellow River sub-basins have been estimated, but this is a topic of continuing research.

After inclusion of each process demonstrated in the model to date, the information can then be used to graphically display the water quality within the GIS database. Graphical representations are shown with respect to water grades defined as follows:

Grade I	> 7.5 mg/L	Drinking Water
Grade II	4 to 7.5 mg/L	Surface Water
Grade III	3 to 4 mg/L	Moderately Polluted
Grade IV	2 to 3 mg/L	Heavily Polluted
Grade V	< 2 mg/L	Seriously Polluted

(Water Resources Assessment for China, 1992)

Use of route assigning functions within ArcView allows this capability (**Figure 11**).

GIS Output of March Dissolved Oxygen Grades
No Reduction Factor Included

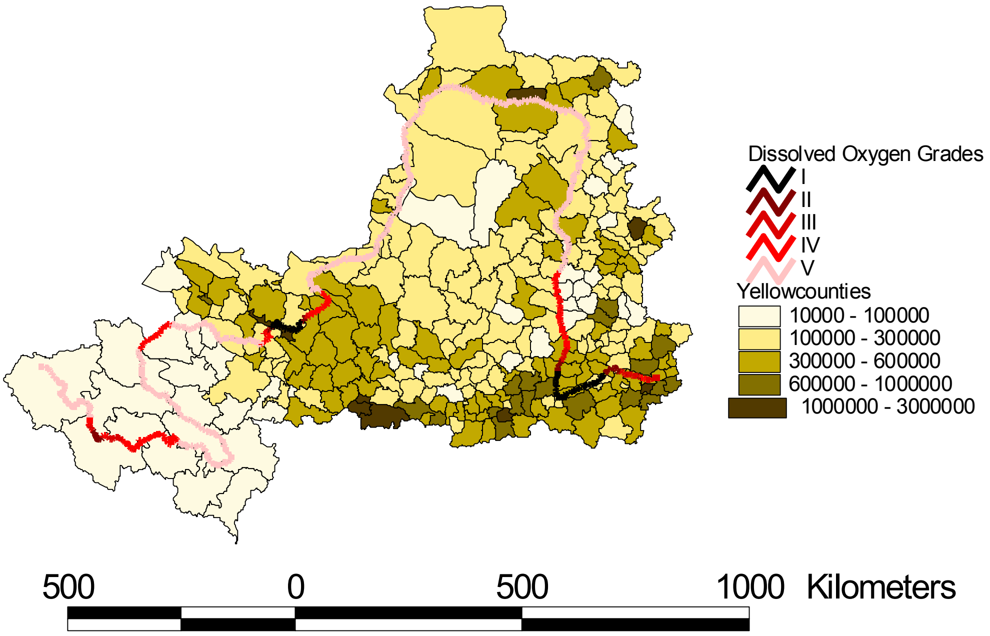

Figure 11

Discussion

The methodology proposed above provides a conceptually realistic way of estimating dissolved oxygen concentration from statistical data. Although the proposed methodology is potentially subject to uncertainty due to limited data sources in addition to simplified mechanisms, it is nevertheless a useful tool to indicate zones where water quality may limit the usefulness of the river.

The BOD and waste generation calculated from each region account for certain topological scenarios and also imply certain assumptions. The concepts of pollution factors and waste factors are simplified means of determining waste generation. With the information currently available, Table 1 indicates only 13% of the BOD generated within the basin comes from sources with point type effluents (i.e. urban wastes, manufacturing wastes). The remaining 87% of BOD generation are introduced as distributed wastes. This balance emphasizes the need for greater understanding of the processes in which BOD is transported into the river.

The initial assumption to specify which census data, hence pollution source, effected which part of the river was to assign each county to the sub-basin in which the majority of the county exists. This assignment scheme worked well for the case when the sub-basins were relatively large compared to the counties. This is the typical case in the downstream reaches which tend to be more populated. This assumption does not give reasonable results when counties are relatively large compared to sub-basins, as is the case in the mountainous regions of the upper reaches of the Yellow River. The effect of this assignment scheme concentrates all the effect of pollution generation into one sub-basin and none to the other sub-basins. However, these minority sub-basins may collectively comprise the majority of the county area. The ‘point load’ effect of this assignment scheme can be seen clearly in the upstream reaches of **Figure 5**. To alleviate this unwarranted assumption, another approach was taken.

First, by overlaying the county boundaries and the sub-basin boundaries to create new regions called *basin-counties*, this allowed pollution generation from each county to be divided into multiple sub-basins if the topography dictates a need. An example of this case would be a large ridgeline within a county that would create a hydrologic dividing line causing flow to exit the polygon in separate directions. To allow for this scenario, the assumption was made that pollution generation is uniform across the county. Without specific knowledge regarding location of population centers within the county, this is a reasonable assumption. However, this is known to be an abstraction of reality due to the typical structure of a Chinese county having one central village surrounded by a rural region. Yet without direct knowledge of where the central village is located, this assumption must be made. Due to the fact that areas which contain major cities often consist of separate administrative units for the urban area, this assumption is considered reasonable for the highest point source pollution generation areas.

The application of the pollution factors and waste factors, as specified by the World Health Organization (1982), is generally an accepted procedure for determining waste generation in a region. However, this type of assessment carries a certain level of inherent uncertainty and must be utilized with caution. For example, the generation of waste from agricultural sources such as cattle, sheep and pigs assumes a feedlot is the primary generation location. By using the statistical census data indicating the number of cows, sheep and pigs in a county, one would incorrectly assume that all the livestock generates waste as the ones residing in feedlots. This assumption may overestimate the amount of waste generated, which may explain the relatively high BOD contribution that sheep and goats were modeled to contribute. Adjustment of these pollution loadings must be based upon knowledge gathered about regional practices, and can be easily incorporated into the model.

Another assumption regarding waste factors was the distribution of point sources and distributed sources among domestic waste generators. Data was acquired on the rural/urban population of each county. Rural populations were assumed to contribute to the distributed pollution generation while urban populations were assumed to contribute to the point pollution generation. Other factors contributing to the point generation for each basin-county were slaughter production, wool production, and dairy production. These processes were assumed to take place in the centralized area of the townships and counties. Conversely, the waste and BOD produced by cattle, pigs and sheep were assumed to contribute to the distributed waste generation. As a methodology, the selected attributes should be assigned to either point or distributed generation types to keep the model relatively simple for poorly defined regions. The attributes selected for this study included generators for which data was available and deemed to have a relatively high waste factor or pollution factor according to the World Health Organization Rapid Assessment (1982). The inclusion of other potential pollution contributors, regardless of the completeness of the data sets, may produce a more realistic result, but was not done here due to a finite length of study and the focus upon developing the methodology.

Estimating the mass input into the rivers from the mass generation of waste is perhaps the most challenging part of this study. The concept of a reduction factor, based upon the travel distance that liquid BOD waste follows to enter the river, is based upon the Streeter-Phelps model. The exponential decay of organic matter along the flow path is assumed to hold true within the sub-basins. Assuming an even distribution of waste production within a basin-county, the mean travel distance the waste would follow to reach the river from any point in the basin-county should be an indication as to what extent the waste has decayed. The wide range of reduction factors implemented exhibited a wide range of effects upon the river, as one would expect. Implementation of a reduction factor of 0.0001 eliminated all anoxic zones predicted in the initial assessments. An across-the-board reduction factor of 0.001 essentially eliminated all zones of depressed oxygen except for the highly populated downstream reaches. Determination of these reduction factors is the main focus of a subsequent study in progress at the time of submitting this paper. To acquire these reduction factors, two techniques are proposed. First, a calibration with actual water quality data would enable adjustment and prediction of the reduction factors in addition to the in-stream decay rates. Utilization of heuristic methods for calibrating this nonlinear system is probably the most useful method, but again this is a topic of continued study. The second method to predict the decay parameters is by comparisons with other systems with similar properties. By determination of the effect of various parameters such as slope, soil type, average precipitation and land-use, reduction factors determined within other similar sub-basins can be applied to sub-basins of interest.

By examining the model results, it became apparent that in almost any scenario (**Figures 5,7,8**) a primary influence on the dissolved oxygen concentrations is the seasonality of the basins hydrology. As indicated in **Figure 6**, the CHARM model predicts an eight-fold fluctuation in total flow between the highest flow of 8500 m^3/sec in August to approximately 1000 m^3/sec in March. Under the assumption of constant loading throughout the year, this results in significant dilution during the high flow months and a critical period occurring during the low flow season. This flow pattern does not account for storage within the basin and is a topic of continued study.

One would expect the assumption that sub-basins can be modeled by an exponential decay to become less appropriate with increased size and complexity of the sub-basin. An illustration of the difference in outcomes due to this assumption is provided by the independent modeling of the Wei He River. The difference that occurred between the dissolved oxygen concentration downstream of the confluence when the Wei He was modeled as any other sub-basin, with no reduction factor, and when the Wei He was modeled separately and used as input to the Yellow River model, was indicated (**Figure 9**). The effect of modeling the Wei He separately decreased the amount of dissolved oxygen in the tributary by 3.3 mg/L (96%) at the confluence. In addition, the peak BOD concentrations at the confluence were reduced by 8.8 mg/L (29%) when the Wei He was modeled separately. These differences indicate that the simplifying assumption of not including a reduction factor to result in significantly erroneous BOD loading. Furthermore, the large differences in dissolved oxygen levels indicate that a simple assumption of a uniform input concentration can produce misleading results at the major confluences. There is obviously a need for estimating the dissolved oxygen concentration at each sub-basin inflow, especially in sub-basins which generate high BOD loads. This combined effect of decreasing the dissolved oxygen concentration and the BOD concentration resulted in both the Wei He and the Yellow River having similar characteristics at the confluence, due to the Wei He passing through high pollution generation regions and contributing 39% of the total flow after the confluence.

Conclusions

The results obtained in this study have contributed to developing the framework for making viable estimations of dissolved oxygen concentrations based only on limited information. The methodology is specific enough to encapsulate the known major processes, yet general enough to not be limited only to application in regions with extensive data and fieldwork. Albeit, many uncertainties exist in ascertaining these types of estimations. The lack of detailed data is a reality in many developing regions in which water quality is a crucial issue in terms of human and ecological health as well as for development.

For the case of the Yellow River in China, the model results are governed by agricultural runoff which dominates the system by means of non-point source pollution. This preliminary assessment has been made without the explicit knowledge of the reduction factors representing decomposition, which are needed to route pollutants to the river. This crucial piece of information is the focus of continuing research and should be properly incorporated into the model once this information is ascertained via calibration with actual water quality data or estimations acquired from basins with similar characteristics.

The rapid assessment procedure described here is less appropriate when exact knowledge of the water quality is required, but does provide a good overview of what regions may be limited by the quality of water and to what extent human impacts may have degraded this natural resource. As a starting point, this model exemplifies areas in need of further detailed studies and demonstrates the major mechanisms that influence dissolved oxygen concentration in major river basins.

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