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# Water quality issues in the Nakdong River Basin in the Republic of Korea

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**Abstract** A framework for evaluating alternative management strategies for the Nakdong River Basin in the Republic of Korea (South Korea) was developed and applied jointly by Argonne National Laboratory in Argonne, Illinois, USA, and the Research Institute of Industrial Science and Technology in Pohang, South Korea. Water from this basin, the second largest in South Korea, supports a total population of more than 13 million people. Rapid industrial expansion, urbanization, and population growth have dramatically increased the demand for water and have severely degraded water quality, particularly near large industrial complexes and in the lower portion of the basin. Management strategies for the entire basin through to the year 2011 were evaluated with a computer model for basin-wide predictions of water flow and quality (HSPF). This continuous-event model was developed and calibrated using site-specific data for the basin over a two-year period (1994–1995) that included periods of both high (monsoonal) and low (drought) flows. Water quality impacts for different wastewater treatment strategies were assessed in terms of biochemical oxygen demand (BOD), nitrogen (N) and phosphorous (P) levels. The results of the study indicate that BOD levels in the main stem of the Nakdong River below the Kumhogang (a major tributary with low flow and heavy pollution loads) cannot be significantly improved by reducing direct BOD loads from point sources along the river. To reduce main stem BOD levels, the nutrient loading to the river must be reduced. In order to reduce these loads, additional advanced treatment methods (i.e., tertiary treatment) must be incorporated in the treatment facilities to remove N and P. The discharge inventory data further suggest that a large portion of N and P loads are derived from non-point agricultural practices. Reduction of these loads is difficult to accomplish and may require extensive modifications in agricultural and land-use practices. The modeling framework developed provides a means to evaluate these and other basin management strategies.

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## Introduction

The Research Institute of Industrial Science and Technology (RIST) in Pohang, the Republic of Korea (South Korea), and the Argonne National Laboratory (ANL) in Argonne, Illinois, USA, developed a framework to evaluate management strategies for the Nakdong River Basin in South Korea (Fig. 1). The Nakdong River Basin, the second largest river basin in South Korea, has a drainage area of about 23,817 $km^2$. The basin extends about 200 km from north to south and about 120 km from east to west (Ministry of Construction and Transportation 1998). Water from the basin supports a local population of about 7.2 million people; water is also diverted outside of the basin to support an additional 6.1 million people. Rapid industrialization, urbanization, and population increases in the last few decades have caused a dramatic increase in the demand for river water, as well as significant deterioration in water quality, especially near large industrial complexes and in the lower basin. These trends are expected to continue unless appropriate management strategies are developed and implemented to ensure adequate water supplies and to restore water quality to levels appropriate for the intended uses.

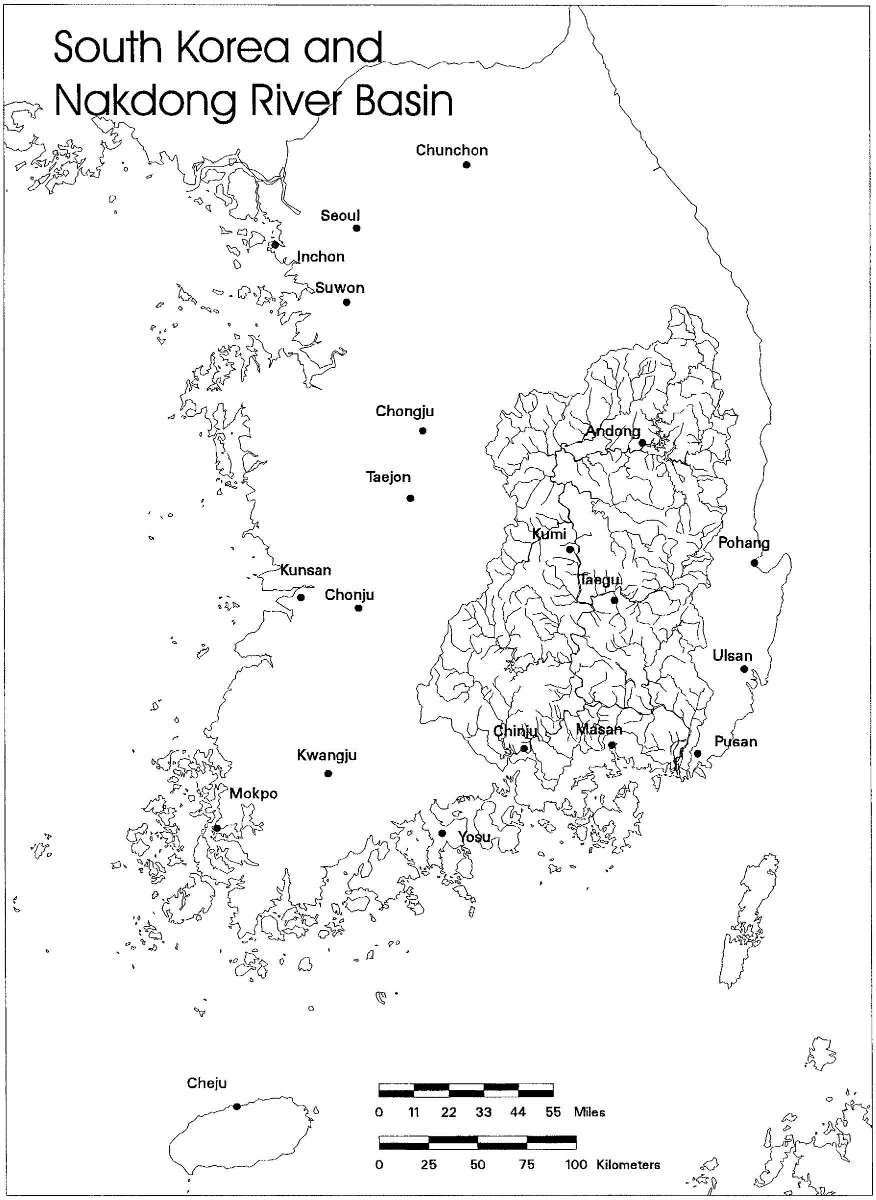


**Fig. 1.** Nakdong River Basin and major cities in Korea

Although South Korea has significant water resources available, it is difficult to ensure a stable supply of high-quality water to meet the demands of a growing population and increasing industrialization because of the extreme temporal and spatial variability of the precipitation. This situation is also true in the Nakdong River Basin.

In addition to the need to provide an adequate water supply, maintaining or improving water quality in the Nakdong River Basin is vital to South Korea. The Nakdong River currently is one of the most eutrophied rivers in the country, with high turbidity and very high nutrient and chlorophyll-a contents, particularly in the southern (lower) portion of the basin. Total nitrogen (N) and phosphorus (P) concentrations are in the hypereutrophic range. In general, water quality and the health of the aquatic communities in the Nakdong River system decrease in a downstream direction, and water quality in the Nakdong River main stem is inferior to most of its tributaries, except the Kumhogang[1], where water quality is very poor. Some of the degradation in water quality and aquatic communities appears to result from contributions of pollutants from the Kumhogang, which exhibits greatly elevated levels of biochemical oxygen demand (BOD), chemical oxygen demand (COD), N, and P, as well as generally depressed levels of dissolved oxygen (DO), relative to the main stem of the Nakdong River and other associated tributaries.

In this paper, we discuss hydrological aspects of the Nakdong River Basin, the development of a numerical model used to simulate future conditions in the basin, different proposed management strategies designed to satisfy water demand and quality requirements, and the potential impacts of these water-management strategies.

[1] "Gang" means major river or major tributary.

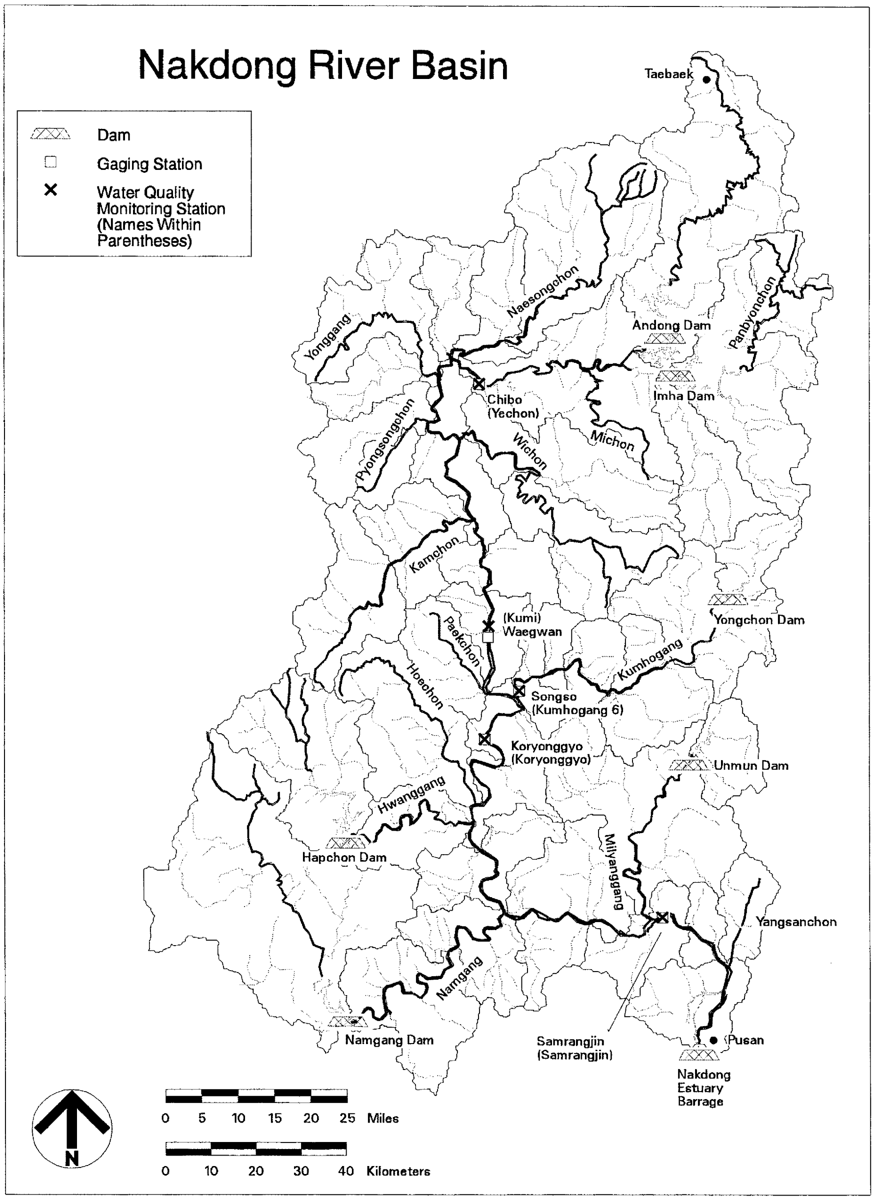


**Fig. 2.** Major tributaries, dams, selected gaging stations, and water quality monitoring stations of the Nakdong River

## Environmental setting

The Nakdong River Basin occupies approximately 23,817 km$^2$, about 24% of the land in South Korea (Ministry of Construction and Transportation 1998). According to 1995 data, about 18.4% of the land in the basin is arable. Rice paddies cover 62% (2,722 km$^2$) of the arable land, and dry fields cover about 38% (1,662 km$^2$). Building sites and industrial complexes cover about 1.8% of the total basin area (430 km$^2$). Forests and fields cover about 69.5% of the total basin (16,554 km$^2$), and other miscellaneous areas comprise 10.3% (2,449 km$^2$) of the basin.

The Nakdong River Basin generally has a temperate climate with four distinct seasons. During the summer, southeasterly winds bring hot and humid air. Monsoon storms that begin in late June provide a large percentage of the annual precipitation for the basin and frequently produce flooding. The annual average precipitation is about 1,231 mm (Ministry of Construction and Transportation 1998). Two-thirds of the annual precipitation falls between June and September. The number of dry and clear days increases during October through December. Only one-fifth of the annual precipitation falls during the period of November through April.

The Nakdong River originates in the vicinity of Taebaek City in Kangwon Province (Fig. 2). The river flows south and through Andong Dam and turns to the west, joining with the Panbyonchon[2] and flowing through Imha Dam. After joining with the Michon and Naesongchon, the main stem of the Nakdong River turns south and joins the Yonggang, Pyongsongchon, Wichon, Kamchon, Paekchon, Kumhogang, Hoechon, and Hwanggang. Meeting the Namgang, the main flow turns east. The Nakdong then turns south after joining with the

[2] "Chon" means minor tributary.

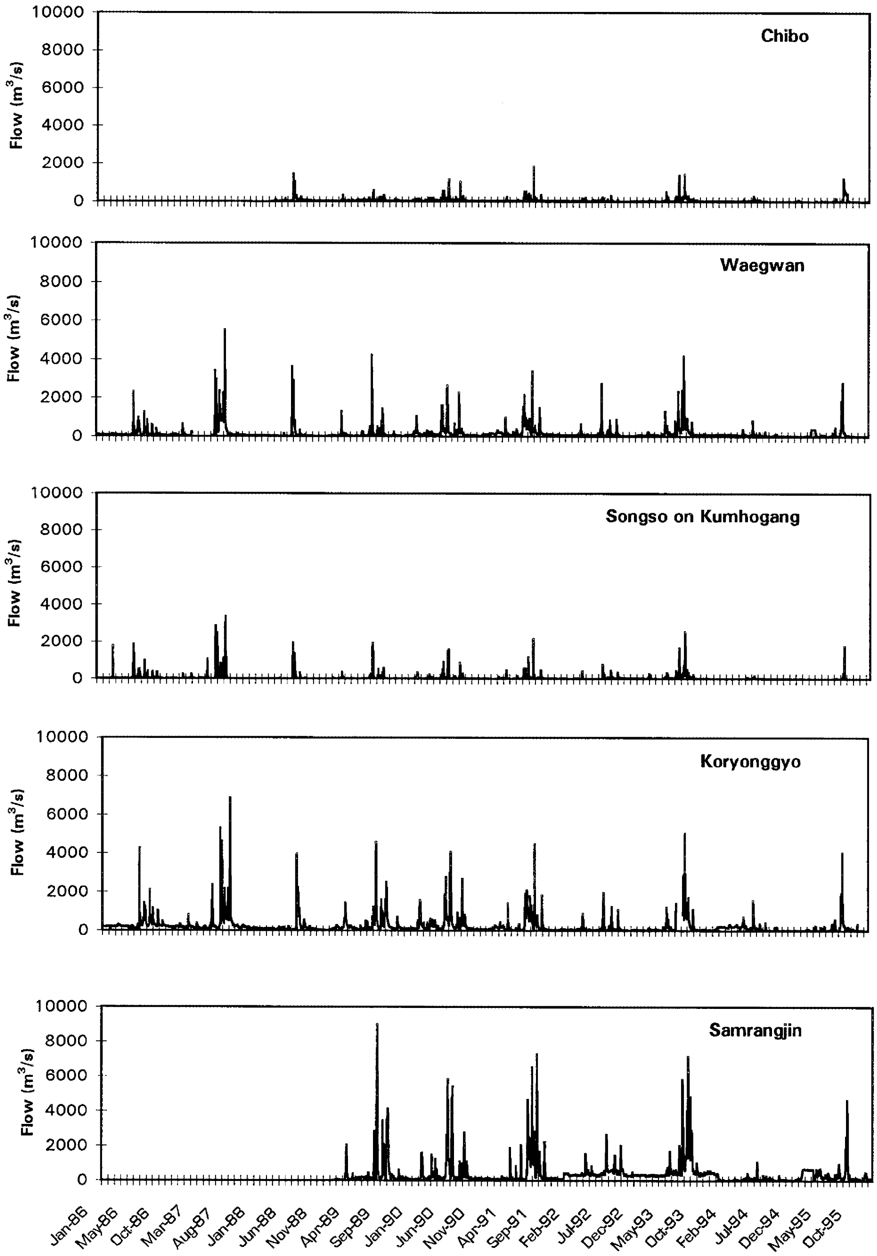


**Fig. 3.** Daily flows at five stream gaging stations in the Nakdong River Basin (1986 to 1995)

Milyanggang. It finally joins with the Yangsanchon and discharges to the South Sea near Pusan after passing through the Nakdong estuary barrage.

The northern portion of the Nakdong Basin is mountainous and steep, while the southern portion has a very small gradient (change in elevation per unit length of river). Flow in the river is highly seasonal; extremely large, short-duration floods occur during the summer monsoon period. Non-monsoonal precipitation and snowmelt produce additional small flow peaks distributed throughout the year. Runoff following precipitation events is very rapid, and the river returns to base flow conditions quickly after each peak. This behavior is illustrated in Fig. 3, which shows flows in the Nakdong River Basin at five gaging stations for a 10-year period from 1986 through 1995. The locations of the gaging stations are shown in Fig. 2.

As of 1995, six major dams and an estuary barrage were located within the Nakdong River Basin (Fig. 2). By 1999, two additional dams had been constructed and another was under construction. These dams are used for water supply storage, flood control, and power generation.

As shown in Table 1, demand for water in the greater Nakdong River region[3] is projected to exceed the supply after the year 2001 (Ministry of Construction and Transportation 1996). In 1994, agricultural demand (mainly for rice paddies) was the largest (52%, 4.5 billion $m^3$/yr) and industrial demand was the smallest (9%, 752 million $m^3$/

[3] Includes Nakdong River Basin and surrounding areas east and south of the basin that receive water from the basin.

**Table 1.** Current and future water demand and supply ($10^6$ $m^3$/year) for the greater Nakdong River region (Ministry of Construction and Transportation 1996)

| Category | 1994 | 2001 | 2006 | 2011 |
|---|---|---|---|---|
| Water demand | 8,569 | 9,496 | 9,974 | 10,562 |
| Domestic | 1,816 | 2,104 | 2,290 | 2,459 |
| Industrial | 752 | 1,177 | 1,180 | 1,277 |
| Agricultural | 4,468 | 4,493 | 4,499 | 4,505 |
| Maintenance | 1,533 | 1,722 | 2,005 | 2,321 |
| Water supply | 8,969 | 9,500 | 9,520 | 9,535 |
| Surface water | 5,022 | 4,940 | 4,933 | 4,921 |
| Groundwater | 614 | 652 | 679 | 706 |
| Dam | 3,333 | 3,908 | 3,908 | 3,908 |
| Existing | 3,333 | 3,333 | 3,333 | 3,333 |
| Under construction | 0 | 575 | 575 | 575 |
| Surplus | 400 | 4 | −454 | −1,027 |
| New development of water resources | 0 | 0 | 810 | 1,410 |
| Surplus after new development | 400 | 4 | 356 | 383 |



yr). The demands for water for domestic use (21%, 1.8 billion $m^3$/yr) and maintenance (18%, 1.5 billion $m^3$/yr) were intermediate. Even with construction of all planned dams, a shortage of about 1 billion $m^3$ is projected by the year 2011. With existing infrastructure, water shortage is expected beginning in the early 2000s because of the construction of large-scale housing and industrial parks in the Pusan and Taegu regions (Fig. 1). To overcome this shortage and secure a stable water supply during periods of drought, a stepwise development of new water resources (e.g., new reservoirs, water re-use) is planned. By 2006, this new development is projected to eliminate a deficit of 454 million $m^3$/yr and replace it with a surplus of 356 million $m^3$/yr; by the year 2011, the surplus will increase to 383 million $m^3$/yr (Ministry of Construction and Transportation 1996).

Within the Nakdong River Basin, about 0.8% (194 $km^2$) of the total land area is used by industry (Ministry of Construction and Transportation 1998). The total of 149 industrial complexes consists of 7 national, 51 regional, and 91 rural industrial complexes. National and regional industrial complexes are located within or near major urban centers, while rural industrial complexes are characterized by a wide spectrum of small-scale industries scattered throughout the basin. The Kumi area in the upper Nakdong basin was developed for electronic industries. The Taegu area, in the middle basin, currently has textile/dyeing industries and is planning to attract high-tech industries. In the lower basin, major industrial complexes, comprising machine, shoemaking, and heavy industries, are located along the coastline.

Agricultural practices in the Nakdong River Basin are important. Agricultural production in Korea has traditionally been dominated by the production of vegetables and rice. In 1997, more than 9 million tonnes of vegetables were raised, and more than 5 million tonnes of rice were produced (Ministry of Environment 1998). Other high-productivity crops include fruits (more than 2 million tonnes), wheat and barley (about 195 thousand tonnes), and potatoes (about 220 thousand tonnes). In 1997, 446 thousand tonnes of nitrogen, 199 thousand tonnes of phosphorus, and 237 thousand tonnes of potassium were used for crop production (Ministry of Environment 1998). Growth in agriculture and the use of fertilizers was most rapid in the 1970s, and has leveled off since about 1991.

Water quality is routinely monitored throughout the Nakdong River Basin. Water quality is, in general, best in the upper basin and worst in the middle and lower basins, where industrialization and urban populations are large. In 1997, the upper regions of the Nakdong main stem had a BOD value of about 1 mg/l (Ministry of Environment 1998). The middle basin had much higher BOD concentrations. For example, in the vicinity of Taegu, the BOD values exceeded 5 mg/l because of the discharges from industrial complexes and the large urban population. Because of biochemical processes that occur as the river flows downstream, the BOD values for the lower regions of the basin are lower than at Taegu. For example, the BOD values at the Nakdong estuary barrage near Pusan are generally 4 mg/l (see Table 2 for water quality criteria for various water uses established by the Ministry of Environment).

In 1997, a total of 2,194,500 $m^3$/day of sewage was treated in the basin and discharged into the river (Nakdong River Environmental Management Office 1998). A 2005 projection is for treatment of 3,695,500 $m^3$/day, including 2,234,000 $m^3$/day of tertiary treatment to remove N and P. The industrial complexes had 11 wastewater treatment facilities; 3 more are planned for completion by 2000. These existing treatment facilities process 422,360 $m^3$/day of industrial wastewater. The three new facilities would treat 22,000 $m^3$/day. The rural industrial complexes had 34 wastewater treatment facilities that processed 20,810 $m^3$ of wastewater/day. Three more facilities were to be completed by 1999 to process an additional 4,000 $m^3$/day. (Data on these facilities were not available at the time of this study.) Four existing feedlot wastewater treatment facilities processed 600 $m^3$/day of wastewater. Nineteen additional facilities that would treat an additional 1,850 $m^3$/day are planned for completion by 2002. There were 37 night soil (human waste) treatment facilities (17 in the upper basin, 9 in the middle basin, and 11 in the lower basin). These facilities processed

**Table 2.** Korean water quality standards for rivers. *Drinking water Class 1*: to be used after simple water treatment such as filtration. *Drinking water Class 2*: to be used after usual water treatment such as sedimentation/filtration. *Drinking water Class 3*: to be used after advanced water treatment in addition to pretreatment. *Natural environment conservation*: conservation of natural environment such as natural scenery. *Fishery water Class 1*: for aquatic biota in oligotrophic water. *Fishery water Class 2*: for aquatic biota in mesotrophic water. *Industrial water Class 1*: to be used after ordinary water treatment such as sedimentation. *Industrial water Class 2*: to be used after advanced water treatment such as chemical treatment. *Industrial water Class 3*: to be used after special water treatment. *Living environment conservation*: To protect public from unpleasantness in daily living. (Ministry of Environment 1998)

| Category | Grade | Application target by intended usage | Standards | | | | |
|---|---|---|---|---|---|---|---|
| | | | Hydrogen ion concentration (pH) | Biological oxygen demand (mg/l) | Suspended solids (mg/l) | Dissolved oxygen (mg/l) | Coliform count (MPN/100 ml) |
| Living environment | I | Drinking water Class 1<br>Natural environment conservation | 6.5–8.5 | <1 | <25 | >7.5 | <50 |
| | II | Drinking water Class 2<br>Fishery water Class 1<br>Swimming water | 6.5–8.5 | <3 | <25 | >5 | <1,000 |
| | III | Drinking water Class 3<br>Fishery water Class 2<br>Industrial water Class 1 | 6.5–8.5 | <6 | <25 | >5 | <5,000 |
| | IV | Industrial water Class 2<br>Agricultural water | 6.0–8.5 | <8 | <100 | >2 | – |
| | V | Industrial water Class 3<br>Living environment conservation | 6.0–8.5 | <10 | No floating debris | >2 | – |
| Protection of human health | All water | Cd: <0.01 mg/l; As: <0.05 mg/l; CN, Hg, Organic P, and PCB: Not to be detected; Pb: <0.1 mg/l; $Cr^{+6}$: <0.05 mg/l; ABS: <0.5 mg/l | | | | | |

4,443 $m^3$/day of human waste. Eleven more facilities are planned for completion by 2001 and would process an additional 640 $m^3$/day (Nakdong River Environmental Management Office 1998).

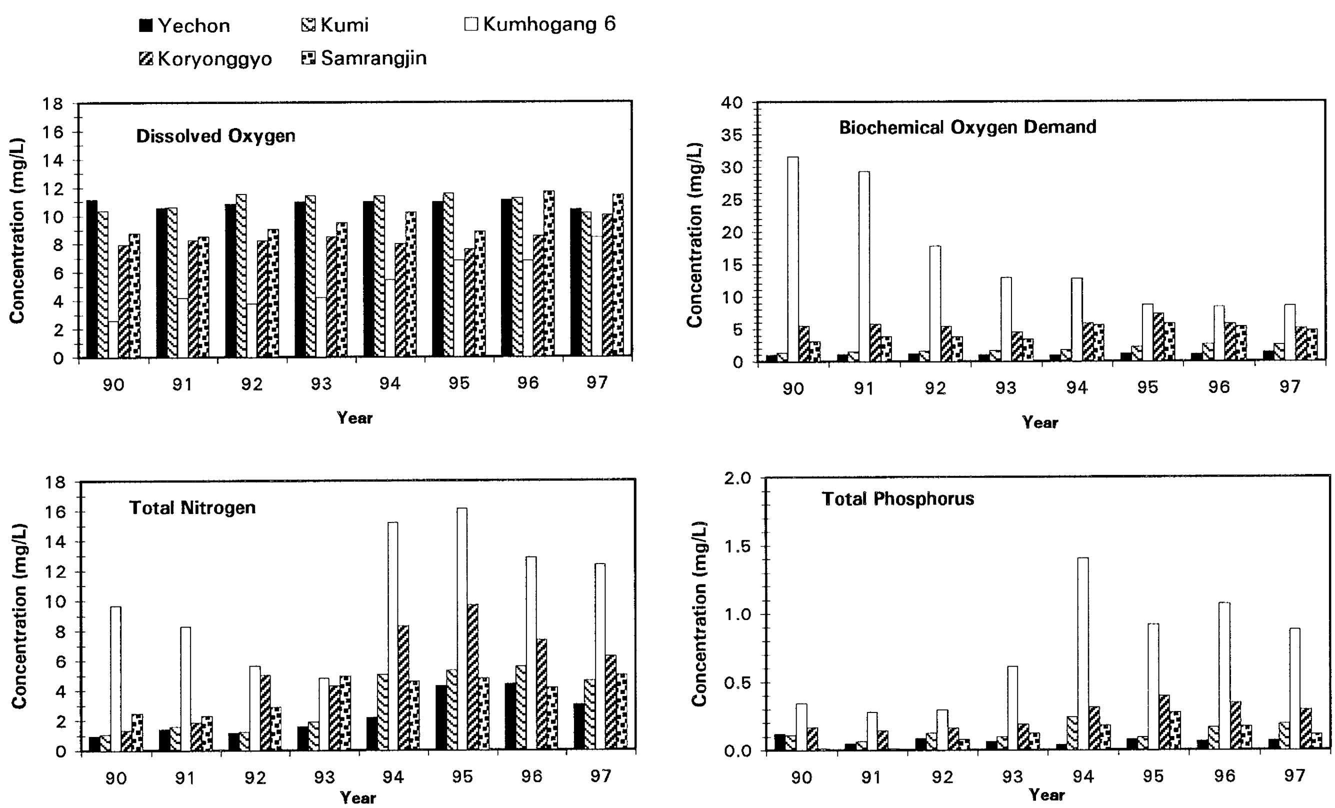


**Fig. 4.** Annual average concentrations of dissolved oxygen, biochemical oxygen demand, total nitrogen, and total phosphorous at five water quality monitoring stations in the Nakdong River Basin

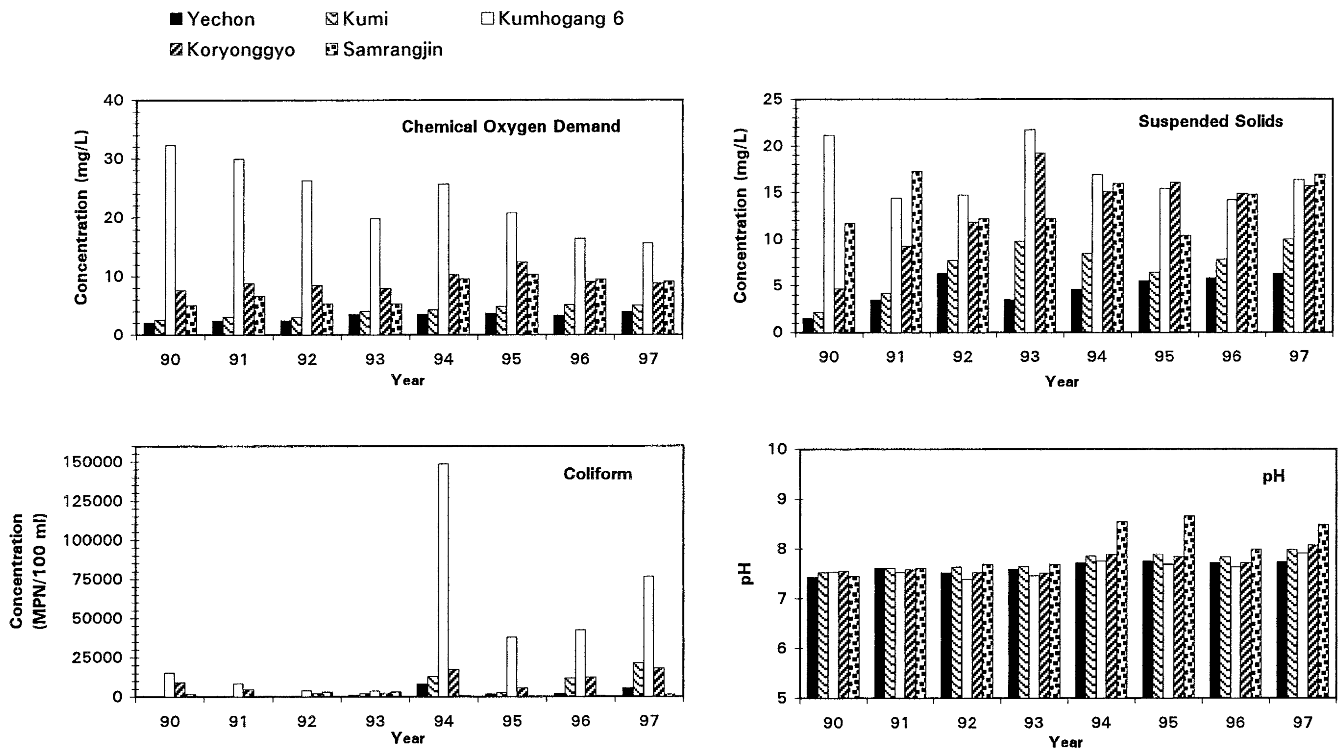


**Fig. 5.** Annual average values of chemical oxygen demand, suspended solids, coliform, and ph at five water quality monitoring stations in the Nakdong River Basin

Figures 4 and 5 illustrate the spatial and temporal variation of water quality parameters (DO, BOD, N, P, COD, suspended solids, coliform, and pH) at selected sampling locations in the main stem of the Nakdong River and one in its major tributary, the Kumhogang, for the years 1990 through 1997. (See Fig. 2 for the locations of these water quality monitoring stations.) The values shown in Figs. 4 and 5 are the yearly averages for each of the sample locations. Along the main stem of the Nakdong River, BOD, COD, N, P, suspended solids, and coliform have gradually increased since 1990. For the Kumhogang, BOD and COD have both decreased since 1990 in response to increased water treatment. However, the concentrations in 1997 were still high (8.6 mg/l and 15.6 mg/l, respectively) and indicative of poor water quality. Peaks seen in water quality parameters in 1994 and 1995 resulted from the drought conditions in the basin.

## Model development

To assess basin-wide management strategies for the Nakdong River Basin, a mathematical model was required to evaluate water flow and quality for existing and future conditions. The model selected for this evaluation was the Hydrological Simulation Program – FORTRAN (HSPF). HSPF was developed by the U.S. Environmental Protection Agency (EPA) to evaluate basin-scale flow and water-quality issues (Bicknell et al. 1996).

For the Nakdong River Basin, an overall strategy was required for the entire basin, which has a total reach length of about 7,440 km. HSPF was designed as a set of modules arranged in a hierarchical structure that permits the continuous simulation of a comprehensive range of hydrological and water quality processes. In HSPF, both flow and water quality are simulated by using a time-series management system for pervious land surfaces, impervious surfaces, streams, and well-mixed impoundments. Its lumped-parameter, empirical approach is well suited to producing results on the scale required to evaluate strategies for the entire Nakdong basin.

For computational purposes, the Nakdong River Basin was divided into 42 sub-basins (Fig. 6). Computer-aided methods for topographic and terrain analysis were used to delineate and characterize the sub-basins. Level 1 Digital Terrain Elevation Data (DTED) for the Korean peninsula obtained from the U.S. National Image and Mapping Agency (NIMA) were used to generate the sub-basins for the HSPF model. The DTED data were processed using the computer model Topographic Parameterization (TOPAZ) (Garbrecht and Martz 1997), which constructed a gradient flow direction grid for the entire basin. A flow-tracking algorithm was then used to determine stream blocks (i.e., a grid block that receives drainage from at least 200 other blocks). In addition, TOPAZ was used to produce a slope model of the entire basin and to delineate each sub-basin watershed.

The next step in model development was to process the results of the TOPAZ model with the Watershed Modeling System (WMS) (Brigham Young University 1996). WMS is a comprehensive computational environment for hydrological analyses. It was developed by the Engineering Computer Graphics Laboratory of Brigham Young University in cooperation with the U.S. Army Corps of Engineers Waterways Experiment Station in Vicksburg, Mississippi.

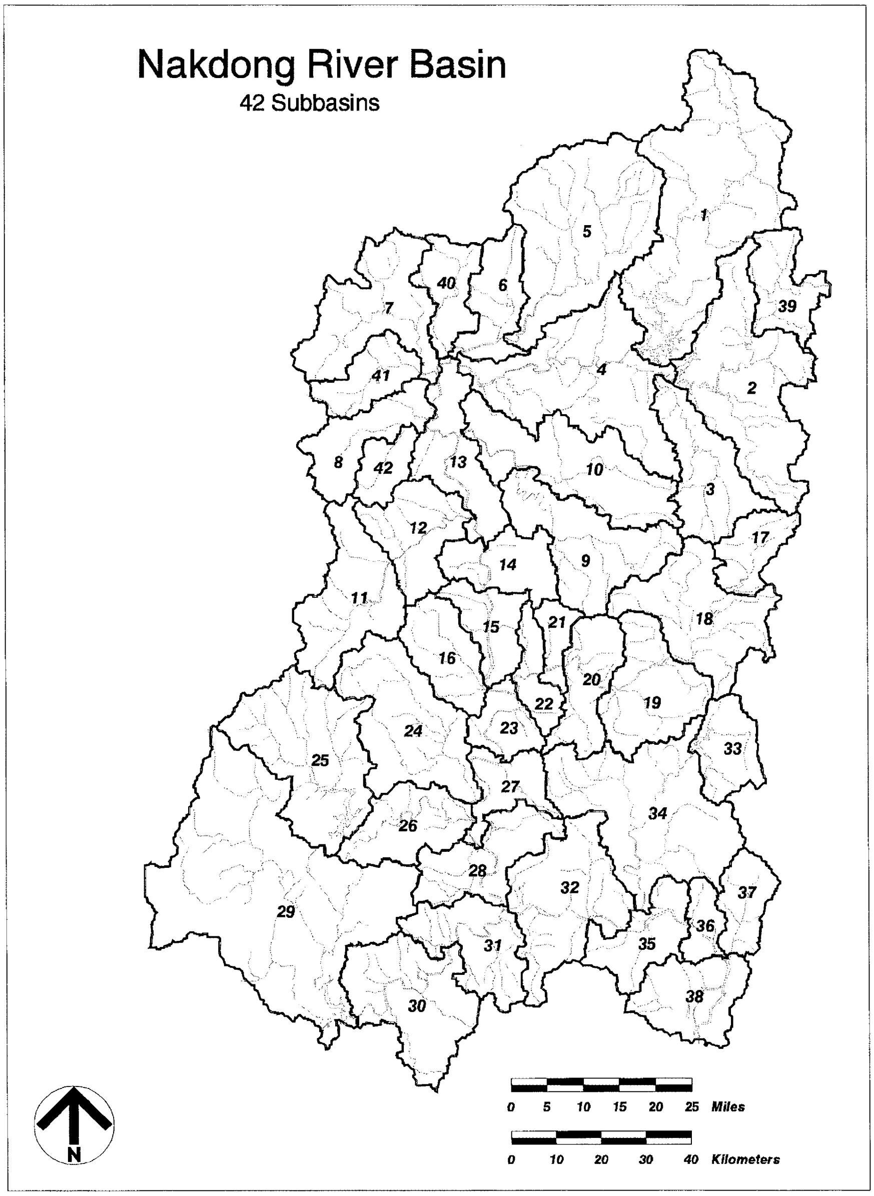


**Fig. 6.** 42 Sub-basins of the Nakdong River Basin

With the flow directions assigned for each DTED point from TOPAZ, the flow accumulation at each point was computed. Streams were identified by DTED points with a flow accumulation value greater than a specified threshold. The resulting stream network was found to be relatively insensitive to the threshold value, so the WMS default threshold value of 200 was used. Once the stream grids had been determined, WMS was used to create vector models of the stream network. A comparison between the TOPAZ-generated streams and streams in the Nakdong River Basin obtained from the Digital Chart of the World showed an excellent similarity.

Polygons were produced from the sub-basin values assigned to the DTED grid. These polygons were converted into a geographic information system (GIS) coverage layer in WMS, which was then used to calculate physical parameters of the sub-basins (e.g., areas, average slopes, and reach lengths). In addition, WMS was used to construct the connectivity logic required by HSPF to couple the 42 independent sub-basins.

The HSPF model was driven by time-series inputs of precipitation, other climatic variables, reservoir operations, water consumptive usage, and pollution loadings, for any given two-year period. A number of important processes were required as input for the HSPF model. For flow, these processes included: precipitation; evapotranspiration; dam operations; and industrial, agricultural, urban, and rural withdrawal and discharge. For water quality, the important processes included net pollution loading from industry, agriculture, and urban and rural areas. Water withdrawals from the Nakdong River Basin included five use categories (domestic, large and small; industrial, large and small; and agricultural). Data for large domestic, large industrial, and agricultural use categories were based on actual daily pumping data recorded at each pumping station (Ministry of Construction and Transportation 1998). Pumping capacities were used to estimate withdrawal data for the small domestic and small industrial use categories by assuming continuous full-load operations. For the calculation of net withdrawal volumes, a return ratio of 80% was assumed for domestic and industrial uses and 35% for agricultural withdrawals (Ministry of Construction and Korea Water Resources Corporation 1977). Withdrawals for water diverted out of the basin were also included. Calibration of the flow aspects of the model was accomplished, in the absence of measured flow data, by using stage data (water level) from 89 gaging stations located on the main stem and major tributaries of the river throughout the basin and reliable rating curves (RIST 1999). If no data existed for the year of interest, flow tables or rating curves for the nearest comparable year were selected.

Dam and diversion release schedules were required in addition to time-dependent flows in the river for model calibration. Dam release data were provided by RIST (1999) for six major dams and one estuary barrage shown in Fig. 2.

All data (e.g., river flow and dam release data, water withdrawal data, meteorological data, pollution load data) for use in the model were converted into an appropriate format and then entered into a watershed data management file using the IOWDM2.3 software (Flynn et al. 1995).

Historical water quality data for BOD, DO, N, and P were used to calibrate the water quality portion of the model. Relatively good calibration was achieved throughout the basin for mean values and event timing, with the largest uncertainties associated with periods of extremely low flow. For these simulations, water quality data for the river were required in addition to source information on pollution loading in the basin. Data were provided in the following categories: domestic, feedlot, land use (subcategories: dry field, rice paddy, forest, ranch, building lot, roads, and miscellaneous), and inland fisheries. In 1995, the largest source of BOD load was from domestic wastewater, followed by land use. Contributions of BOD loads from fishery and industrial sources were relatively minor. Land use and domestic wastewater categories contributed most of the total nitrogen discharges to the Nakdong River Basin. Feedlots, industrial, and fishery sources contributed only small fractions of the total nitrogen loads. The largest contributors of total phosphorus were land-use and domestic discharges. Model-predicted concentration levels in the river were, in general, in good agreement with the field data.

The Base Case was established from the HSPF results for the 1994–1995 calibration period. This case provided a basis for evaluating the effects of different basin management strategies related to conditions projected for the years 2001, 2006, and 2011. As mentioned earlier, this two-year simulation includes periods of low flows, as well as periods of high flows. The years 1994 and 1995 were selected for the simulations because drought conditions existed in the basin, and 7Q10 (i.e., 7-day, 10-year low flow) conditions were present for statistical analyses (Viessman et al. 1972).

Water quality in the Nakdong River Basin over the two-year Base-Case period showed a general trend of increasing concentrations toward the lower end of the basin, while reaches in the upper end of the basin had lower concentrations of BOD, N, and P. Dissolved oxygen levels were high in the entire basin, with the exception of the Kumhogang, which had calculated values below 8 mg/l. Levels of N and P were very high throughout most of the basin.

An evaluation of model responses indicated that changes in direct BOD loadings did not result in major changes in BOD concentrations in the lower reaches of the river. This suggests that a significant percentage of the BOD in the lower reaches of the river resulted from benthic BOD releases, and BOD caused by high levels of N and P, rather than from direct BOD pollution loads.

To evaluate management strategies for the Nakdong River Basin, predictions were required for water demand and pollution loading. The management strategies are presented in the following section. Projected water withdrawals from the Nakdong River Basin for the years 2001, 2006, and 2011 (see Table 3) were derived using the municipal and industrial water supply plan (Ministry of Construction and Transportation 1996) and the 1995 withdrawal data (Ministry of Construction and Transportation 1998).

For each basin, future daily-average pollution loads for the years 2001, 2006, and 2011 were projected on the basis of projected future population or other appropriate statistics, and a constant unit pollution load factor, with the exception of BOD in the domestic category. Table 4 presents a summary of these projections for the entire Nakdong River Basin. Projected human population data for future years were obtained by interpolating the projected data for the years 1996, 2001, 2006, and 2011 (Ministry of Construction and Transportation 1996). Data for future domestic wastewater treatment facilities were

**Table 3.** Water withdrawals from the Nakdong River Basin in 1995 and those projected for 2001, 2006, and 2011 ($10^6$ $m^3$/year) (Ministry of Construction and Transportation 1996; Ministry of Construction and Transportation 1998)

| Category | 1995 | 2001 | 2006 | 2011 |
|---|---|---|---|---|
| Domestic | 1,368 | 2,000 | 2,233 | 2,270 |
| Industrial | 367 | 410 | 410 | 447 |
| Agricultural | 685 | 685 | 685 | 685 |
| Total | 2,420 | 3,095 | 3,328 | 3,402 |

**Table 4.** Pollution loads in 1995 and those projected under the three different scenarios (kg/day) (RIST 1999)

| Pollutant | 1995 (base case) | Scenario | 2001 | 2006 | 2011 |
|---|---|---|---|---|---|
| BOD | 455,163 | 1 | 492,626 | 508,940 | 505,826 |
| | | 2 | 408,289 | 418,024 | 420,730 |
| | | 3 | 411,596 | 418,024 | 420,730 |
| N | 194,127 | 1 | 216,416 | 231,639 | 231,723 |
| | | 2 | 205,470 | 218,354 | 211,546 |
| | | 3 | 205,644 | 218,354 | 211,546 |
| P | 17,843 | 1 | 19,496 | 20,660 | 20,667 |
| | | 2 | 18,241 | 19,110 | 18,656 |
| | | 3 | 18,257 | 19,110 | 18,656 |

based on information compiled by Nakdong River Environmental Management Office (1998). The number of domestic animals and the acreage distribution for various land uses were conservatively assumed to remain constant on the basis of recent trends of decreasing pollution loads from these sources (RIST 1999). Pollution loads from inland aquaculture facilities were assumed to be the same through the year 2011. Actual pollution load data used for industrial sources were compiled by RIST (1999). Future pollution loads were estimated on the basis of current unit pollution loads back-calculated from the current pollution load data and increments in building area for planned industrial complexes (Ministry of Construction and Transportation 1996). The daily-average pollution load data thus obtained were assigned to vary temporally in order to closely simulate expected conditions. Domestic and industrial loads were assumed to vary monthly, depending on their respective monthly intakes. Feedlot loads were assumed to be the same throughout the year. Inland fishery loads were assumed to be constant only from April to October, when the fishery is active. Loads from land-use practices were assumed to occur only on rainy days with a daily rainfall of greater than 10 mm.



### Management strategies

Three alternative management strategies for the treatment of domestic wastewater were evaluated with the HSPF model for the years 2001, 2006, and 2011. The standard of comparison for the evaluations was the Base Case for years 1994 and 1995 discussed above. The alternative management strategies differed from the Base Case to reflect future conditions related to pollution loads, diversions, and domestic wastewater treatment in the following ways (Nakdong River Environmental Management Office 1998):

- Scenario 1: Pollution loads and water diversions, including consumptive use, in each of the 42 sub-basins were projected for the years 2001, 2006, and 2011 on the basis of projected population increases, land-use patterns, industrial growth, and dam operations plans. For this scenario, it was assumed that no additional wastewater treatment facilities would be added after 1995. This scenario served as the "No-Action Scenario."
- Scenario 2: Base-case conditions were modified to be consistent with the Ministry of Environment (1996) Plan. For this plan, additional secondary and tertiary treatment facilities would be added to the basin, modifying the pollution load projections of the No-Action Scenario with respect to BOD, and with respect to N and P in basins with tertiary treatment facilities. (These tertiary treatment facilities would only treat N and P).
- Scenario 3: The conditions of scenario 2 were modified by adding domestic wastewater treatment facilities according to the 1998 Revised MOE Plan (Nakdong River Environmental Management Office 1998). Although the timing of introducing additional facilities differs from that of scenario 2, overall basin loadings were similar.

Current (1995) pollution loads and those projected under each scenario are presented in Table 4.

### Results and discussion

While the detailed time-series results for water quality parameters provide a basis for comparing the effects of the differing management strategies reflected in the future scenarios, they do not allow ready access to the general temporal and spatial changes related to different strategies. The challenge of synthesizing the model results for several parameters produced at 15-minute intervals for two years at 42 sub-basins into meaningful summary information is large.

It is common in basin-wide modeling, where time-series outputs are generated, to develop one or more indices or measures that can be calculated to indicate various system behaviors. Many different kinds of indices are possible, ranging from simple averages to exceedance value based measures (Aramaki and Matsuo 1998).

For the purpose of this study, a single index was derived for interpretation of model results for multiple scenarios. Other indices are possible and should be investigated depending on the question being addressed. The index chosen was selected to emphasize the basin response to a particularly "stressful" situation for water quality in the system – the low-flow conditions exhibited during the May 1995 period of the Base Case. For the Base Case and each scenario, the monthly average of the daily average concentrations of BOD, N, and P in May 1995 were computed for sub-basins 4, 14, 22, 23, and 32, and were normalized by Base-Case concentrations for sub-basin 4 (Andong Basin), which is near the headwaters of the Nakdong River and is relatively free of impacts from industrialization and growth.

Comparisons of model results, in terms of the water quality indices, under the three scenarios for years 2001, 2006, and 2011, with those for the Base Case are shown in Figs. 7 through 9 for BOD, N, and P, respectively. The figures only show data for scenarios 1 and 2, because the differences between scenarios 2 and 3 were found to be small and would not have been readily discernable.

Five sub-basins were selected for displaying time-series results for the Nakdong River. These sub-basins include two that are upstream of the confluence with the Kumhogang: sub-basin 4 was chosen to show an area with little impact and sub-basin 14 to show the water quality in the main stem of the Nakdong River before the loadings from the Kumhogang are added (sub-basin 22). Sub-basin 23, the main stem of the Nakdong River immediately downstream of the confluence with the Kumhogang, was chosen to show the impacts of the Kumhogang on the main stem. Sub-basin 32 was chosen to show the water quality of the main stem in the lower reaches of the river near Pusan. Use of these sub-basins makes it possible to observe the spatial and temporal variability of water quality indices throughout the basin. For BOD, the following trends are indicated in Fig. 7:

1. The highest predicted BOD indices are associated with the Kumhogang sub-basin (sub-basin 22); predicted BOD indices in main stem sub-basins downstream of

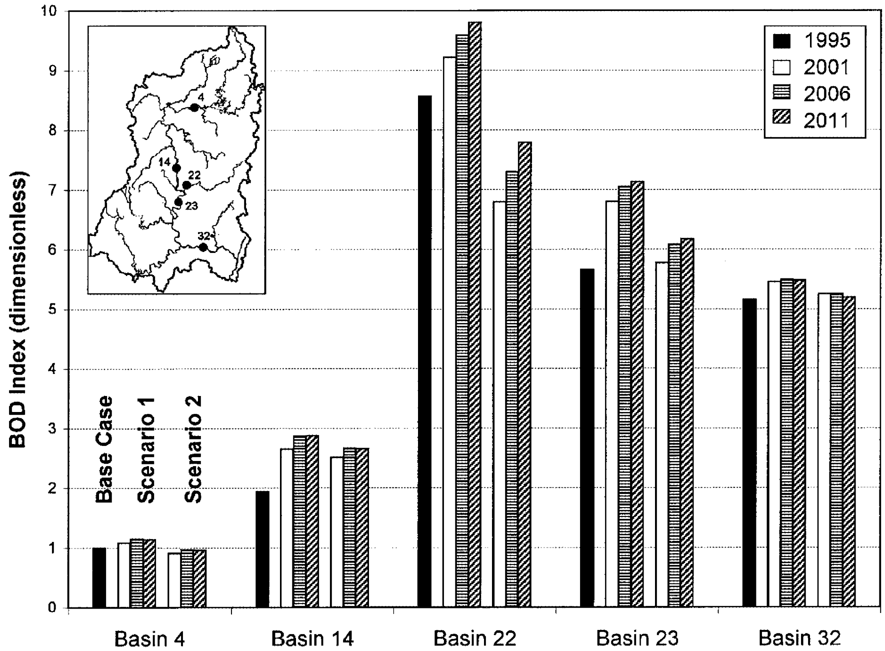


**Fig. 7.** BOD index (dimensionless) predicted for May for selected sub-basins

the Kumhogang are about twice as high as in upstream sub-basins.

2. BOD indices predicted for the No-Action Scenario (scenario 1) exceed those of the Base Case in 2001 and continue to increase with time.
3. The inclusion of additional domestic wastewater treatment facilities in scenario 2 results in significant reductions, compared with scenario 1, in the BOD index in the Kumhogang sub-basin (sub-basin 22) and the sub-basin immediately downstream (sub-basin 23), but only small reductions in the BOD index upstream of the Kumhogang (sub-basins 4 and 14) and at the farthest downstream sub-basin (sub-basin 32).

For N and P, the following trends are noted in Figs. 8 and 9:

1. The indices for N and P are highest in sub-basins 22 and 23, which are on the Kumhogang and the main stem of the Nakdong River immediately downstream of the Kumhogang, respectively, and the No-Action Scenario indices are greater than those of the Base Case.
2. For scenario 2, which features the addition of tertiary treatment facilities to remove N and P, predicted N and P indices are lower than for scenario 1.
3. The additional reduction, under scenario 2, in nutrient indices observed near the Kumhogang from 2006 until

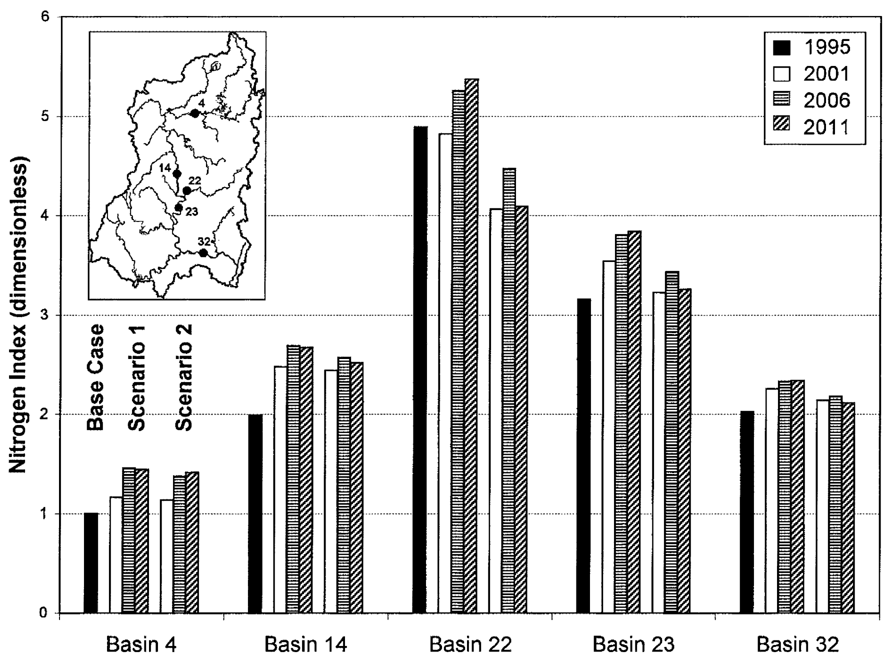


**Fig. 8.** Nitrogen index (dimensionless) predicted for May for selected sub-basins

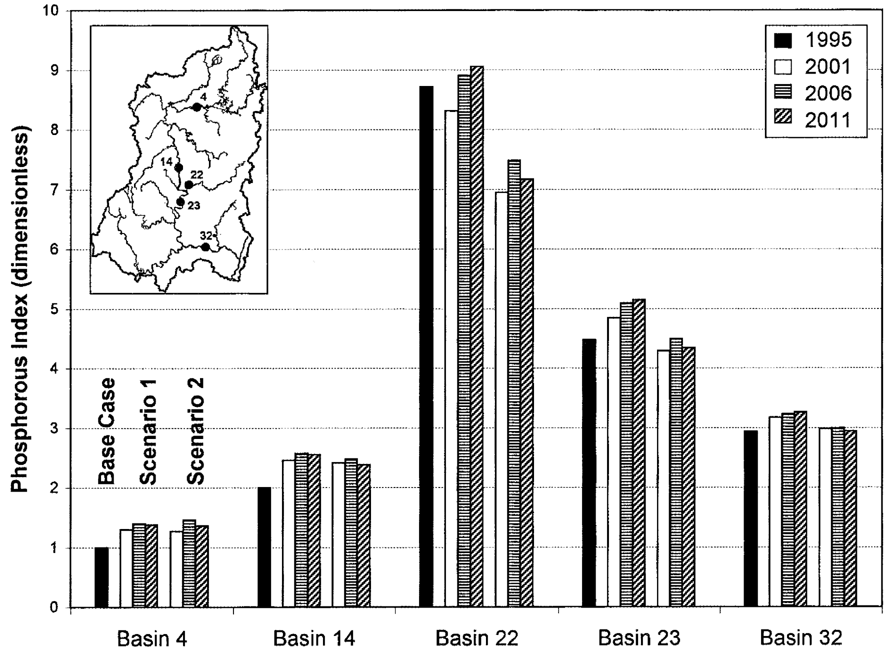


**Fig. 9.** Phosphorous index (dimensionless) predicted for May for selected sub-basins

2011 is a result of a larger portion of domestic wastewater being treated using tertiary treatment.

4. Except for sub-basins 22 and 23, which are on the Kumhogang and the main stem of the Nakdong River immediately downstream of the Kumhogang, respectively, nutrient indices show only small decreases in values relative to the No-Action Scenario (scenario 1).

As indicated by the above model results, management strategies associated with scenarios 2 and 3 would have a positive effect on water quality in sub-basins in the vicinity of the Kumhogang. However, the model predictions also indicate that acceptable water quality in the Kumhogang cannot be achieved by only reducing the pollution load. Base flows in the Kumhogang are not sufficient to maintain acceptable water quality, even in the case of near-zero pollution loadings from point sources. Large upstream diversions out of the Kumhogang contribute to the low base flows. To obtain acceptable water quality, current diversions must be decreased to allow increased flow in the lower portion of the Kumhogang. Without this increased flow, acceptable water quality may not be achieved in the Kumhogang through the addition of wastewater treatment facilities.

BOD levels in the main stem of the Nakdong River below the Kumhogang cannot be significantly changed by decreasing direct BOD loads to the river. The model computations indicate that BOD levels in the lower portion of the main stem of the river are largely generated by phytoplankton growth, which is driven by the high levels of N and P, rather than BOD loads.

To decrease the BOD level in the main stem, nutrient loading to the river must be decreased. Because levels of N and P are very high in the Nakdong River Basin, and the model results indicate that the limiting factors for organism growth under these conditions are light and temperature, rather than nutrient levels, large decreases in nutrient loads would be required to change substantially the BOD levels in the river. These reductions have implications for long-term management strategies in the Nakdong River Basin because the removal of N and P from domestic and agricultural waste loads requires more advanced treatment methods (i.e., tertiary treatment to remove N and P) than those required to reduce BOD.

The model results further indicate that the future water quality concerns in the Nakdong River Basin will be driven by non-point sources of pollution. The majority of nutrient loads (i.e., N and P) are derived from agriculture or land-use practices. Loads from non-point sources are difficult to control and treat. Extensive changes in agricultural and land-use practices would be required to change these loads appreciably. Studies are ongoing to address possible approaches in this area.

## Conclusions

The results presented have significant management implications. First, it is unlikely that BOD levels in the main stem of the Nakdong River below the Kumhogang can be significantly reduced by decreasing direct BOD loads to the river. Second, in order to decrease BOD levels in the river, N and P nutrient loads from domestic and agricultural sources need to be reduced. For domestic wastewater treatment, this reduction will require more advanced methods that incorporate tertiary treatment to remove N and P. Agricultural wastes that contribute N and P non-point source loads to the river are more problematic. Such loads have been traditionally difficult to control and treat, and may require extensive changes in agricultural and land-use practices.

Within the Kumhogang, consumptive water use and diversions are very high and contribute to the poor water quality predicted by the study. At times, there is no flow in this important Nakdong River tributary. For the Kumhogang, efforts need to focus on increasing the flow under dry season conditions (e.g., modifying diversions), and simultaneously decreasing non-point source nutrient loading.

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