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GIS-Based Reach File Generation for Efficient TMDLs Implementation

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ABSTRACT. The ability to generate stream network data is essential to conducting fast searches and accurate analyses to obtain various types of environmental information on individual streams required to implement a Total Maximum Daily Loads (TMDLs) program. This study presents a major concept, an algorithm, and a procedure to build such stream network data, the Korean Reach File (KRF), based on a geographic information system (GIS). For the generation of the KRF's graphic data, a 1:25,000 scale nationwide river/stream map, a watershed map, and a polygon type administrative district map were utilized to delineate stream flow lines, split stream reaches, and assign unique identifiers. To generate the KRF's attribute data, we designed attribute tables for all the graphic data. All the attributes were inputted to each item of graphic data according to designed attribute input rules and the KRF was generated in a shapefile format. To evaluate the accuracy of the graphic data, we compared the stream lengths of the KRF on national level streams with actually surveyed stream lengths. The study results showed the graphic and attribute data that were generated for the four major river basins with a total stream length of 21,163 km. The Mean Absolute Percentage Error (MAPE) was about 3.8%, and we confirmed that the KRF network data were generated with relatively high spatial accuracy. The KRF's applicability for the TMDLs was also discussed with exam-ples. In the future, a GIS-based management system using the KRF should be developed to support TMDLs more efficiently.

Keywords: geographic information system (GIS), Korean Reach File (KRF), Total Maximum Daily Loads (TMDLs), stream network analysis

1. Introduction

The Ministry of Environment (MOE) in South Korea has adopted and carried out a Total Maximum Daily Loads (TMDLs) program since 2002, and it has collected much pollution source data and water quality data nationwide to support the TDMLs (Kong, 2005). Then, to enable efficient management and sharing of collected data, many computerization studies regarding construction of databases and development of information systems have been pursued since 2003 (NIER, 2011). However, it was impossible to search and analyze water environment data spatially on the developed system; it only enabled users to ask for water pollution source data and water quality data with exact coordinates or unique identifier codes. In addition, stream network analysis that considered stream connectivity was not supported in the existing systems. Therefore, the necessity of a geographic information system (GIS) based data mining and analysis technology has been increasing.

GIS technology has already been used to find the causes of water pollution problems and predict the future water quality in many other environmental studies in the past (Karimipour et al., 2005; Luk et al., 2004; Huang and Chang, 2003) because a GIS is effective in handling complicated spatial information that is essential for many environmental studies as well as in providing platforms for integrating various models, systems, and interfaces (Huang et al., 1999; Lovejoy et al., 1997). The United States Environmental Protection Agency (EPA) has utilized the GIS in implementation of TMDLs since the 1990s. In this process, it has developed spatial framework data such as the River Reach file (RF) to efficiently integrate and provide all the relevant data and information in a GIS environment.

The RF is a topographical database of surface water features; it defines the stream branch unit, which is a stream reach, and represents the topographical relationship between reaches (USEPA, 1994a, b). The RF consists of graphic data and attributes data. Graphic data were produced through the division of stream network into line type features and generalization of the stream into the units of the stream reach. And attribute data were generated by assigning unique identifiers to individual stream reaches and linking various attributes of relevant watershed sections. Recently, the RF has been included in the National Hydrography Dataset (NHD), which has been developed for integrated management of spatial data on surface water for more diverse use.

The RF has been utilized for GIS-based management of water environment information in the TMDLs studies (Cooter et al., 2010; Ries et al., 2010). The spatial data representing

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Table 1. Characteristics of Four Major River Basins in South Korea

Basin division	Main river name	Drainage area A_w [km^2]	Basin perimeter L_p [km]	Basin river length L_b [km]	Effective basin width R_b (= A_w/L_b) [km]	Form factor R_f (= A_w/L_b^2) [-]	Major city	Population number in city [Thousand People]	Population density in city [People/ km^2]
Han River Basin	Han River	23,293	1,124	494	47	0.10	Seoul	10,026	16,567
							Incheon	2,750	2,664
Nakdong River Basin	Nakdong River	23,702	1,097	512	46	0.09	Busan	3,464	4,509
							Daegu	2,477	2,803
Geum River Basin	Geum River	9,914	738	389	25	0.07	Daejeon	1,527	2,827
Yeongsan/ Seomjin River Basin	Yeongsan River	3,470	435	135	26	0.19	Gwangju	1,506	3,005
	Seomjin River	4,914	671	223	22	0.10	-	-	-

Table 2. List of Collected Spatial Data

Spatial data name	Type	Format	Feature class	Scale	Year	Custodian
River/stream map	Vector	Shapefile	Polygon	1:25K	2005	Ministry of Environment (MOE)
Dam location map	Vector	Shapefile	Point	1:25K	2009	MOE
Weir location map	Vector	Shapefile	Point	1:25K	2009	MOE
Administrative district boundary map	Vector	Shapefile	Polygon	1:5K	2009	MOE
Standard watershed boundary map	Vector	Shapefile	Polygon	1:25K	2002	MOE

the stream flows have been used in connection with various measurement data and watershed data. The Watershed Assessment, Tracking & Environment Results (WATERS) is one of the representative systems for managing and providing water environment information (USEPA, 2013a). Furthermore, it has been used for modeling of water quality prediction such as Better Assessment Science Integrating point and Non-point Sources (BASINS), SPAtially Referenced Regressions On Watershed attributes (SPARROW) and RiverSpill model (USEPA, 2001,2013b; Ierardi et al., 2004; Dewald and Roth, 1997).

However, in South Korea, there were no similar stream network data to support the TMDLs program implementation. Therefore, it must be produced before South Korea develops relevant GIS-based information systems as in the U.S. However, following the U.S. example without considering the conditions of South Korea presented difficulties. There was no stream network map available to be used as reference material in South Korea. In addition, it was not possible to use the GIS-based stream network data extraction method using Digital Elevation Model (DEM) data because most rivers and streams are relatively narrow and short. Thus, stream network data should be produced with a new approach and examined through empirical research.

The aim of this study was to generate the GIS-based stream network data, the Korean Reach File (KRF), to support the TMDLs program implementation. To build the KRF's graphic data, we proposed a generation method based on previous studies (Kwon et al., 2012; Lee et al., 2013). A stream line map was generated to represent the stream flows. Then, individual stream reaches were defined and delineated using the stream line map. In determining the stream reaches, point-type graphic data were created at the start and end points of each stream reach. As a major reference to build the KRF, we reviewed the U.S. EPA's Reach File version 3 (RF3) (USEPA, 2003a, b; Lee, 2005). The accuracy of the KRF's graphic data was proven to be acceptable. Finally, we discussed the applicability of the KRF to facilitate the Korean TMDLs.

2. Study Area and Spatial Data Collection

2.1 Study Area

The target area of this study was the four major river basins in South Korea consisting of Han River, Nakdong River, Geum River, and Yeongsan/Seomjin River. Table 1 shows the features of each basin, and Figure 1 shows the distribution of streams of each basin and the boundaries of the four major river

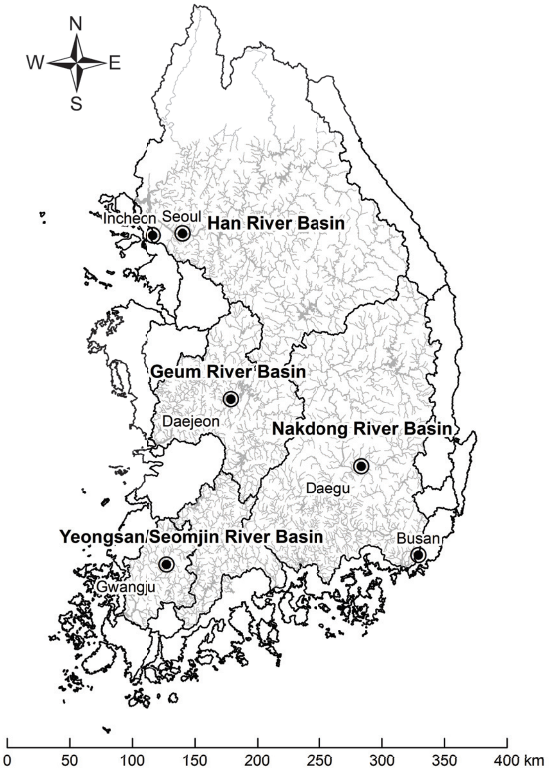


Figure 1. Study area: four major river basins and river streams in South Korea.

basins. The total size of the four river basins is about 65,293 km^2 which is 64.5% of the national territory (MLTM, 2013). They include major metropolitan areas that contain more than 60% of the total population of the nation. Considering the recent deterioration of water quality and higher demands to mitigate water pollution, the four river basins are appropriate for this study.

2.2 Collection of Spatial Data

Spatial data related to the generation of the KRF were collected with the cooperation of the MOE. Table 2 shows the list of collected spatial data for this study. The river/stream map in a vector format that represents the stream's left and right boundaries was obtained as required for drawing a stream flow line map. That data was in a shapefile format including polygon type data with a scale of 1:25,000 and was normally utilized by the MOE for TMDLs studies. In addition, point type shapefiles showing the location of dams and weirs as well as polygon type shapefiles showing the administrative district boundaries and basin boundaries were collected from the MOE to split stream reaches and generate relevant attributes.

3. Generation of KRF's Graphic Data

3.1 Definition of Graphic Data

The generation of a dataset based on a network data model is required to carry out GIS based network analysis. The widely used network data model 'arc-node model' (Kim, 2010) was adopted. This model structurally stores the information on the relationship of collection and connection of the line and point type data. This also enables definition of network directionality and the identification of upper and lower streams (Maidment, 2002; Kim et al., 2004a, b; Kim, 2010). This was considered as suitable to generate the KRF's graphic data based on the arc-node model since the KRF should also support stream network analysis. The line type data were generated by delineating the stream flow lines from the river/stream map and splitting them into the units of the stream reaches. Finally, the point type data were generated through screen digitizing of inlet and outlet points of each stream reach.

3.2 Generation Method of Graphic Data

In preceding studies, a Digital Elevation Model (DEM) was generally used in the delineation of stream flow lines. Stream flow lines for specific basins were delineated through assigning appropriate threshold values depending on the experience of the expert analysts (Maidment, 2002; Maidment and Djokic, 2000; Saunders, 1999; Tarboton et al., 1991; Jensen and Domingue, 1988). However, this method could generate network data for sections where actual streams do not exist or, on the other hand, network data might not be created in a section where a stream actually exists. This implies that the network data generated using the DEM can have more or fewer stream branch points than actually exist, thus leading to distortion of the network shape compared to the actual stream as well as distortions of the stream length. This shortfall of DEM could undermine the accuracy of the network analysis.

In this perspective, the stream flow lines represented by the line type feature of the KRF were delineated using 'the skeletonizing method for the vector data' proposed by Lee et al. (2009, 2013) and Park et al. (2010). The skeletonizing method for the vector data extracts the center points of each stream and connects them. It extracts all the vertices on the stream boundary line then extracts the center points of the maximum inscribed circle adjoining them. The center points of the maximum inscribed circle extracted are considered as the vertices of the stream flow line and the stream flow lines are created by connecting them. The center points and connection lines created unnecessarily in the process of flow line drawing were removed through visual inspection at post-processing phase. In particular, if a loop occurs due to the islands in the stream, then any extraneous lines were deleted so that only one flow exists in one stream.

Upon completing the flow line delineation, each stream flow line was divided into the unit of stream reach. The stream reach was defined to represent the stream section divided by the 'location of the stream confluence', 'location of the stream water source and drainage points', 'location of dams and weirs', and 'location of stream boundary points on a vector type stream map'. The 'location of the stream confluence' was defined as the location of the points where the stream joins a branch as it flows down from the upper stream water source of all streams according to the stream flow direction. The 'location of the

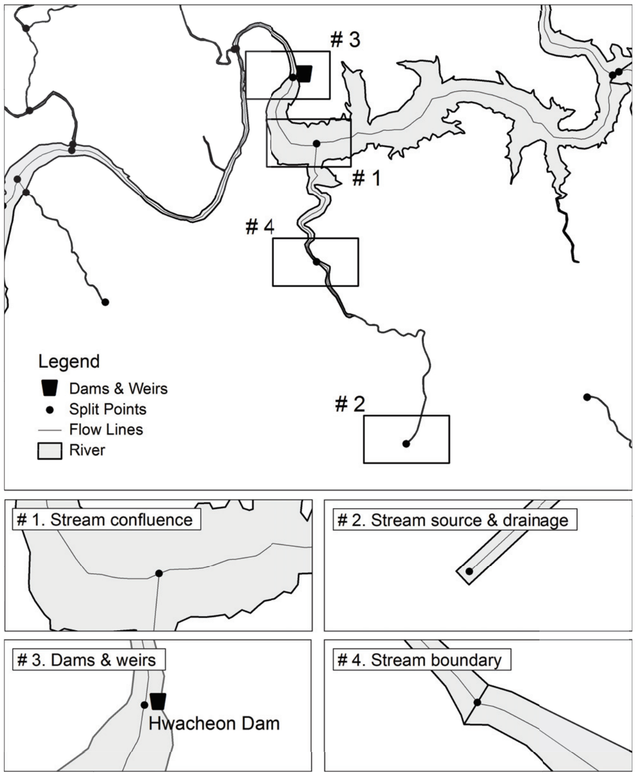


Figure 2. Example of split flow lines.

stream water source and drainage points' was defined as the uppermost water source point and the lowermost water drainage point of each stream. The 'location of dams and weirs' was defined as the location of a point where it exists on the stream flow line most closely after overlaying with the point type graphic data showing the location of existing dams and weirs. The 'location of the stream boundary point on a vector type river/stream map' was defined as the location where the delineated stream flow line and stream boundary cross each other. Figure 2 shows the four examples mentioned above.

Since these split standards clarify the split location of a stream reach, it is possible to obtain results with a certain degree of accuracy at a predictable level of error even if graphic data are generated by numerous different researchers. In addition, it is advantageous for clarifying the definition of the topological relationship since it enables the clarification of the connectivity, inclusion and neighborhood relationship between points (inflow and outflow points of each stream reach), lines (stream flow line) and polygons (river/stream map). It is also advantageous in terms of generation and inspection of graphic data since the split point can be easily checked through visual inspection. The stream flow lines split in the unit of stream reach were stored as line type graphic data of the KRF, and split points were stored as the point type graphic data of the KRF through screen digitizing with visual inspection.

3.3 Assignment of the Unique Identifier

Upon completing delineation of the graphical data of the stream network, it is necessary to assign a unique identifier for each graphic feature of the KRF. This unique identifier should be defined by the specific rules and should be generated for individual objects without duplication. The unique identifier should explain the main attributes of each object so that it can be used as the search key for relational joins to other programs or databases similar to the EPA's RF. The unique identifier of the EPA's RF consists of the Hydrologic Cataloging Units (CU) number, a Segment (SEG) number and a Marker Index (MI) number (USEPA, 1994a,b).

Rivers and streams in South Korea are separated and defined comprehensively considering humane, social, administrative and historical factors, along with hydrological factors. Each stream is assigned a unique code based on the Water Management Information Standard enacted by the government for effective information management regarding rivers and streams (MOCT, 2004). The various items of stream environment information are also stored in a database based on the 'standard stream code'. Accordingly, it was considered that this standard should also be reflected in the KRF for the utilization of database information in connection with the KRF.

Figure 3 shows the composition of the standard stream code adopted in South Korea. The standard stream code consists of a 2-digit basin number, a 1-digit stream level classification code for identifying management agencies (0: national government, 1: local government level 1, 2: local government level 2), and a 4-digit sequential unique number assigned to each stream based on the confluence of the basin which is sequentially allocated in downstream order. The basin number of the standard stream code corresponds to the CU of the EPA's RF and the sequential unique number to the SEG of the EPA's RF, respectively. Additionally, this stream code can be used as the unique identifier by simply adding MI value at the end of the standard stream code.

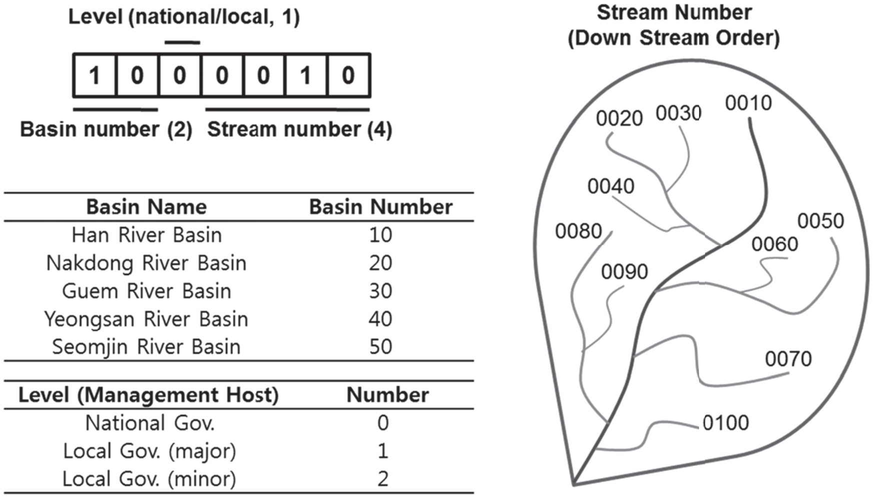
The MI of the KRF was defined as the percentage value of the accumulated distance from the lowermost downstream to the split point to the total length of the specific stream based on the standard stream code. Equation (1) is the formula to calculate the MI_n value of the n^{th} stream reach R_n included in the stream with the length of S_l. Figure 4 shows an example of the calculated MI values. The MI value of the uppermost stream reach is defined as 99.99999:

$$MI_n = \left(\sum_{i=1}^{n} R_i - R_n\right) / S_l \times 100(\%) \tag{1}$$

In this method, the stream flow lines are delineated from the polygon type river/stream map and split on the stream boundary according to the fourth split rule. This is different from the conventional method to delineate stream flow lines using DEM. Therefore, the stream reaches can be additionally generated in the connection area of the 'main stream to a tributary stream' in the KRF. However, such stream reaches additionally generated cannot be assigned a unique identified code with the combination of standard stream code and MI. This is due to the fact that the stream reach of a 'main stream to a main

Table 3. Attribute List of Point Type and Line Type Data for the KRF

Class	Attributes of point type data	Attributes of line type data
Theme attributes	Feature ID, Catalog Units (CU), Segments (SEG), Marker Index (MI), Reach's node ID	Feature ID, CU, SEG, MI, Upstream reach's MI, Tributary(TRIB), Classification of main and tributary stream, Basin's name, River's name, Classification of main and tributary stream as river's name, Reach's line ID, River's length, Reach's length/cumulative length, Presence of connected reach, Presence of start/end reach, (Reach's) Type/Level, Updated date
Location attributes	Coordinates of X & Y	(Inflow/Outflow, Max./Min.) Coordinates of X & Y
Topology attributes	Number of connected reaches, Connected downstream reach's ID, Name of TMDL's watershed, Standard watershed's code, Administrative district's code	Administrative district's code, Inflow direction of main upstream, Inflow direction of complement reach, Presence of divergent reach, (Inflow/Outflow) Name of TMDL's watershed/Standard watershed's code/Administrative district's code/Reach's node ID, (Upstream left/Upstream right/Complement/ Downstream/Divergence) Reach's ID



Basin Name	Basin Number
Han River Basin	10
Nakdong River Basin	20
Guem River Basin	30
Yeongsan River Basin	40
Seomjin River Basin	50

Level (Management Host)	Number
National Gov.	0
Local Gov. (major)	1
Local Gov. (minor)	2

Figure 3. Composition of the standard stream code in South Korea.

stream' and the stream reach of a 'main stream to a tributary stream' can share one MI value at the confluence point, so that the same unique identifiers are to be assigned to such reaches. Figure 5a shows the problem of the unique identifier at the confluence point sharing the same MI value. In this figure, stream reach (A) of 'a main stream to a main stream' and stream reach (B) of 'a main stream to a tributary stream' are found to have the same identifier of '1002710 38.13853'.

Therefore, a 1-digit tributary (TRIB) code to identify the order of the tributary was added to the unique identifier of the line type graphic data to solve the problem of the duplicated unique identifier. The unique identifier of the point type graphic data was defined as the combination of the 7-digit standard stream code and 8-digit MI value while the unique identifier of the line type graphic data was defined by adding the TRIB code. Figure 5b shows an example of an assigned unique identifier to each stream reach. The numeric '1' is assigned for the main stream reach to represent the main stream flow while '2' for the connection stream reach of the 'main stream to a tributary stream, respectively. Figure 6 shows the composition of the unique identifier assigned to point type data and line type data in the KRF.

4. Generation of KRF's Attribute Data

4.1 Consideration of EPA's RF Attribute

To define the attributes of the KRF, the attributes of the EPA's RF have been reviewed. The EPA's RF attributes have been changed continuously during the development period

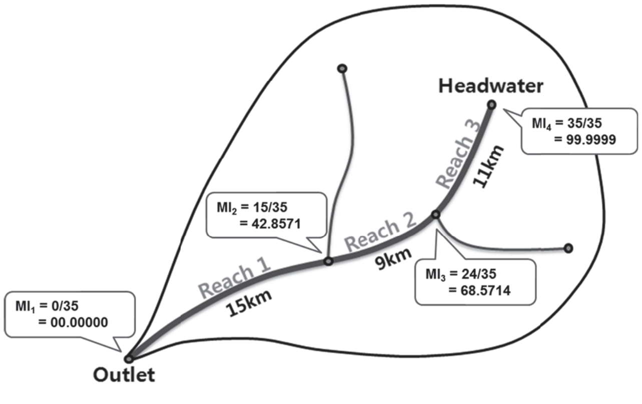
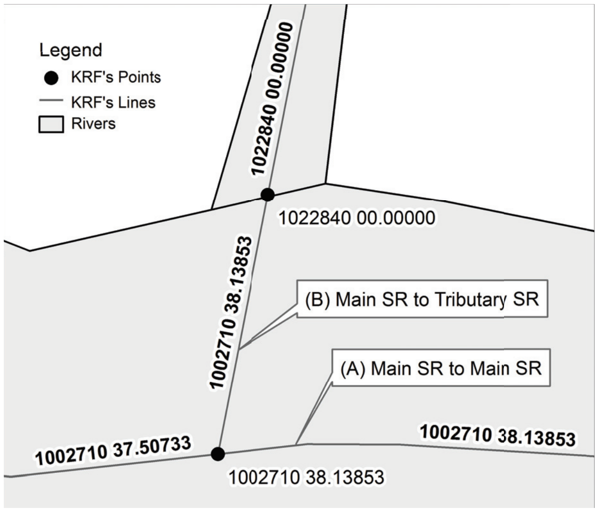


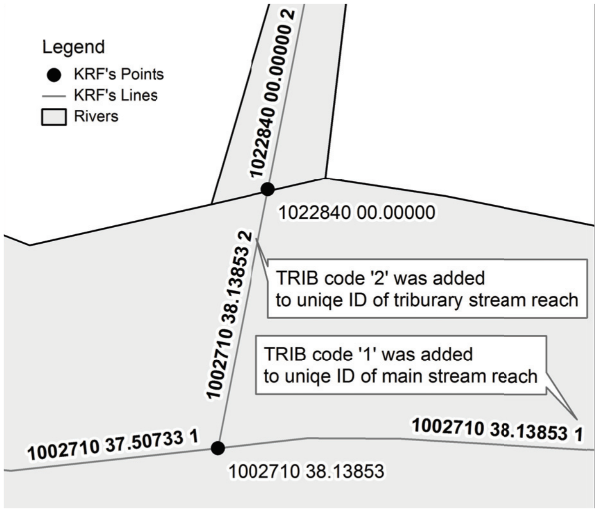
Figure 4. Example of calculated Marker Index values.

over 30 years. Accordingly, the topological information has been updated to enhance the spatial search and analysis use in the RF3. The detailed attributes for hydrographical and water quality features on specific stream reaches were stored in a separate database and utilized for the users. This approach minimized the amount of attribute information to be stored with graphic data and reduced the processing speed required for the GIS analysis.

The attributes in the RF3's version have been adopted for the KRF attribute design considering that various databases of hydrology and water quality information have already been built by individual agencies. It was more effective to connect and utilize the RF3's attributes rather than to build new databases for the KRF. In addition, it seemed to be advantageous to store the minimum attribute data with graphic data to enhance the operational performance for the application purposes.



(a) Sharing of MI values at the stream confluence



(b) Example of assigned unique ID for each graphic feature

Figure 5. Assignment of unique identifier for KRF's graphic features.

4.2 Analysis of Korean TMDLs Works

To define the detailed attributes for the KRF application, the Korean TMDLs work was analyzed. The TMDLs work guide and configuration details of MOE's database were reviewed. The pollution source and pollutant loading data have been managed by the administrative district units of each major watershed through MOE's database. In most database tables, the 'basin name', 'basin code', '(legally defined) administrative district name' and '(legally defined) administrative district code' were used in the database. They were also used for information searches and queries. In this regard, to take into account the connectivity and compatibility with TMDLs, the 'basin name', 'basin code', 'administrative district name' and 'administrative district code' were included in the KRF attributes.

4.3 Attribute Modeling

Attribute modeling was carried out in three categories: 'theme attributes,' 'location attributes' and 'topology attributes'. The theme attributes were modeled to contain the minimum amount of the thematic information in attributes so that stream environment data related to TMDLs could be efficiently managed using network data. In particular, the attributes such as 'stream name', 'stream code', 'basin name' and 'administrative district name' were included because they play key roles in relational joins with related databases. For the location attributes, 2-dimensional XY coordinates of the TM coordinate system were included in the attributes for the easier identification of the location of each feature object and fast search of the location. In addition, the minimum and maximum values of the XY coordinates were included in the attributes so that the Minimum Enclosing Rectangle (MER) method (Kim, 2010) could be applied for more efficient spatial indexing and searching. The topology attributes were modeled in reference to the EPA's RF3 attributes. They can be used for upstream and downstream navigation, the calculation of accumulated stream length, and the extraction of target stream reaches. Table 3 summarizes the details of the attributes defined through the attribute modeling process.

4.4 Attribute Design and Input

The field name, data type, length and definition of the KRF attributes were defined in the attribute table through a logical design process. Tables 4 and 5 show the results of attribute design of the KRF's point type and line type data. Attributes for all the graphic data were generated using ArcGIS Desktop 9.3.1 based on the attribute design. The location and topology attributes, which can be generated using the 'Calculate Field Geometry' and 'Identify' function, were automatically generated. In addition, the 'Spatial Join' and 'Overlay' functions were used to automatically input the theme attributes. Some attributes that could not be generated automatically were manually generated using the 'Editor' function.

5. Results and Discussion

5.1 Result of Graphic Data Generation

Figure 7 shows the generated results of the KRF's graphic

Table 4. Specifications of the Attribute Table for Point Type Data

No	Attribute	Field name	Type	Length	Definition
1	Feature ID	FID	CHAR	various	The serial number of features
2	Geometry	SHAPE	GM	various	The geometric information of reach's node
3	Catalog units	CU	CHAR	2	2-digits sub-basin code defined by K-WATER (ex.10)
4	Segments	SEG	CHAR	7	7-digits standard river/stream code (ex.100010)
5	Marker index	MI	CHAR	8	The ratio of the cumulative length from the outlet point of segment to the node point in each segment (ex.00.0000)
6	Reach's node ID	RCHNODEID	CHAR	16	The unique ID for reach's node with combination of SEG & MI
7	Number of connected reaches	NUM_RCH	NUM	1	The number of connected reaches at reach's node
8	Connected downstream reach ID	D_RCHID	CHAR	18	The connected downstream reach's line ID with reach's node
9	X-coordinate	TM_X	NUM	10.3	The X-coordinate of reach's node (Bessel/TM)
10	Y-coordinate	TM_Y	NUM	10.3	The Y-coordinate of reach's node (Bessel/TM)
11	TMDL watershed name	T_UW_NM	CHAR	30	The name of TMDL's watershed containing reach's node
12	Standard watershed code	K_SW_CD	CHAR	6	The code of standard watershed containing reach's node
13	Administrative district code	ADM_CD	CHAR	10	The administrative district's code (according to legal standard)

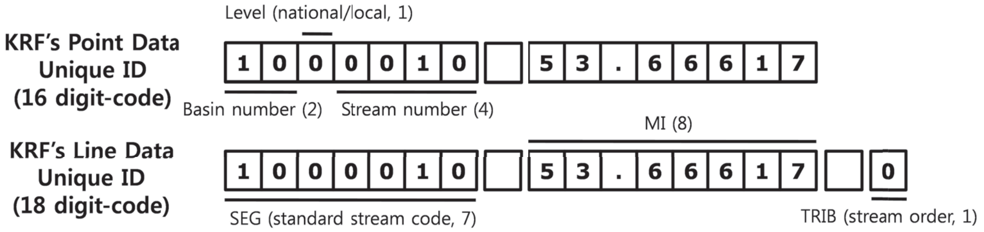


Figure 6. Composition of KRF's unique identifier.

data. A total of 7,047 stream reaches were created for a total of 2,402 streams using the standard stream code, and their total length was approximately 21,163 km. Among them, the number of stream reaches representing the pure flow line except the connection stream reach, which is the 'main stream to the tributary stream' created by splitting on the stream boundary, was a total of 4,762 and their total length was 20,570 km. The point type data were generated with the combination of a total of 7,052 nodes. Considering that the whole streams flow into to the sea at five locations (Han River, Nakdong River, Geum River, Youngsan River and Seomjin River), the total number of nodes should be more than the total number of stream reaches by five, and the result satisfied this. This confirms that the point type and line type data of the network dataset generated by the arc-node model were suitable.

5.2 Result of Accuracy Evaluation on Graphic Data

Table 6 shows the comparison result of the stream length from the KRF graphic data and the Korean River List for the major national streams. The Korean River List is the report that summarizes the actual field measurement data of the stream lengths periodically to establish the basic plans of river maintenance by the Ministry of Land, Transport and Maritime Affairs (MLTM) in South Korea. This study regarded the stream lengths from the Korean River List (MLTM, 2008) as the true values and the accuracy of the graphic data was evaluated by comparing the stream length from the KRF with that of the Korean River List.

The comparison was made for a total of 39 major national rivers and streams. As summarized in Table 6, there was no significant difference between the stream length of the Korean River List (A) and the stream length of the KRF (B). While some stream sections had a higher variation in stream length, we considered the magnitude of the difference not to be significant based on the result of the difference ratio to stream length (|A - B|/A). The Mean Absolute Percentage Error (MAPE) for the target streams was about 3.8% and it was verified that accurate graphic data were generated. Additionally, from the scatter plot of Figure 8 showing the trend of the stream length difference, most of the stream lengths generally coincided with the actual surveyed values. Figure 8 also shows that all the streams were clustered closely along a straight line, suggesting that accurate graphic data were generated regardless of the

Table 5. Specifications of the Attribute Table for Line Type Data

No	Attribute	Field name	Type	Length	Definition
1	Feature ID	FID	CHAR	various	The serial number of features
2	Geometry	SHAPE	GM	various	The geometric information of reach's line
3	Catalog units	CU	CHAR	2	2-digits sub-basin code defined by K-WATER (ex.10)
4	Segments	SEG	CHAR	7	7-digits standard river/stream code (ex.100010)
5	Marker index	MI	CHAR	8	The ratio of the cumulative length from the outlet point of segment to the end node point of reach in each segment (ex.00.0000)
6	Upper marker index	UPMI	CHAR	8	The ratio of the cumulative length from the outlet point of segment to the start node point of reach in each segment (ex.99.99999)
7	Tributary class	TRIB	CHAR	1	The geometric classification of main and tributary stream
8	Basin name	BASIN_NM	CHAR	30	The name of basin containing reach
9	Stream name	STR_NM	CHAR	30	The name of river/stream containing reach
10	Tributary class by stream name	STR_NMTRIB	CHAR	1	The classification of main and tributary stream by stream's name
11	Reach line ID	RCHLINEID	CHAR	18	The unique ID for reach's line with combination of SEG, MI & TRIB
12	Segment length	SEG_LEN	NUM	10.3	The length of river/stream of each segment
13	Reach length	RCH_LEN	NUM	8.3	The length of instant reach
14	Cumulative length	CUM_LEN	NUM	10.3	The cumulative length from the outlet point of segment to the end node point of reach in each segment
15	Reach connectivity flag	R_FLAG	CHAR	1	The flag of reach's connectivity with downstream
16	Terminal reach flag	T_FLAG	CHAR	1	The flag of terminal reach
17	Start reach flag	S_FLAG	CHAR	1	The flag of start reach
18	Reach type	RCH_TYPE	CHAR	1	The type of reach
19	Level	LEV	CHAR	1	The level of river/stream defined by government
20	Administrative district code	ADM_CD	CHAR	10	The administrative district's code (according to legal standard)
21	Upstream inflow direction	USDIR	CHAR	1	The inflow direction of main upstream
22	Upstream left reach SEG	ULSEG	CHAR	7	The upstream left reach's SEG
23	Upstream left reach MI	ULMI	CHAR	8	The upstream left reach's MI
24	Upstream left reach TRIB	ULTRIB	CHAR	1	The upstream left reach's TRIB
25	Upstream right reach SEG	URSEG	CHAR	7	The upstream right reach's SEG
26	Upstream right reach MI	URMI	CHAR	8	The upstream right reach's MI
27	Upstream right reach TRIB	URTRIB	CHAR	1	The upstream right reach's TRIB
28	Complement reach direction	CDIR	CHAR	1	The inflow direction of complement stream
29	Complement reach SEG	CSEG	CHAR	7	The complement reach's SEG
30	Complement reach MI	CMI	CHAR	8	The complement reach's MI
31	Complement reach TRIB	CTRIB	CHAR	1	The complement reach's TRIB

Table 5 (Continued)**.** Specifications of the Attribute Table for Line Type Data

No	Attribute	Field name	Type	Length	Definition
32	Divergence	DIVERGENCE	CHAR	1	The presence of divergence reach
33	Downstream reach SEG	DSSEG	CHAR	7	The downstream reach's SEG
34	Downstream reach MI	DSMI	CHAR	8	The downstream reach's MI
35	Downstream reach TRIB	DSTRIB	CHAR	1	The downstream reach's TRIB
36	Divergent reach SEG	DIVSEG	CHAR	7	Divergent reach's SEG
37	Divergent reach MI	DIVMI	CHAR	8	Divergent reach's MI
38	Divergent reach TRIB	DIVTRIB	CHAR	1	Divergent reach's TRIB
39	Upstream inflow node ID	U_NODEID	CHAR	16	The upstream inflow node's ID
40	Downstream outflow node ID	D_NODEID	CHAR	16	The downstream outflow node's ID
41	Upstream inflow point X-coordinate	U_TM_X	NUM	10.3	The X-coordinate of inflow point from upstream (based on Bessel/TM)
42	Upstream inflow point Y-coordinate	U_TM_Y	NUM	10.3	The Y-coordinate of inflow point from upstream
43	Downstream outflow point X-coordinate	D_TM_X	NUM	10.3	The X-coordinate of outflow point to downstream
44	Downstream outflow point X-coordinate	D_TM_Y	NUM	10.3	The Y-coordinate of outflow point to downstream
45	Maximum X-coordinate	MAX_TM_X	NUM	10.3	The maximum X-coordinate of reach's extent
46	Maximum Y-coordinate	MAX_TM_Y	NUM	10.3	The maximum Y-coordinate of reach's extent
47	Minimum X-coordinate	MIN_TM_X	NUM	10.3	The minimum X-coordinate of reach's extent
48	Minimum Y-coordinate	MIN_TM_Y	NUM	10.3	The minimum Y-coordinate of reach's extent
49	Upstream inflow point TMDL watershed name	U_T_UW_NM	CHAR	30	The TMDL's watershed name of inflow point from upstream
50	Downstream outflow point TMDL watershed name	D_T_UW_NM	CHAR	30	The TMDL's watershed name of outflow point to downstream
51	Upstream inflow point standard watershed code	U_K_SW_CD	CHAR	6	The standard watershed code of inflow point from upstream
52	Downstream outflow point standard watershed code	D_K_SW_CD	CHAR	6	The standard watershed code of outflow point to downstream
53	Update date	UPDATE	DATE	8	The updated date

stream scale. Furthermore, the skeletonizing method used in this study can be used in various network analysis studies as well as stream information management in the future because of its higher accuracy.

In some streams, such as Munsan Stream, Kyeongan Stream, Banbyeon Stream and Deokcheon River, there was a noticeable difference with the actual length being higher than 10%. This may have been caused by the time difference between the generation time of the river/stream map used for KRF and the Korean River List. The river/stream map was generated in 2005 while the Korean River List dates from 2008. There have been river maintenance work conducted since 2005 that may have caused shape changes of the rivers. This emphasizes the importance of currents in the source data used.

5.3 Result of Attribute Data Generation

Attributes were generated for all stream reaches according to the attribute table of the KRF to have 13 attributes for point type data and 53 attributes for line type data (figure 9). Since the KRF attribute contains the topology information of connectivity among the stream reaches, it may also be used for network analysis. This will be useful for searching for upper streams or lower streams that may affect the water quality of relevant drainage systems in a specific stream reach. In addition, the keys that can be used for relational joins with various databases were included in the form of theme attributes. This enables us to provide various environment information data for individual stream reaches upon completing GIS based information systems.

5.4 Discussion on Applicability in TMDLs implementation

The Korean TMDLs are legally defined to measure water quality at the end or junction of rivers which are designated by the MOE. The discharge of the pollution sources in the upper

Table 6. Comparison Results of the Stream Length of the KRF Graphic Data and the Korean River List

No.	Basin Name	River Name	Standard Stream Code	Length in Korean River List (A) [km]	Length in Korean Reach File (B) [km]	Length Differences (A-B) [km]	Absolute Percentage Error |A-B|/A*100 [%]
1	Han River Basin	Han River	1000010	265.4	276.7	-11.3	4.3
2		Dal Stream	1000870	15.1	15.2	-0.1	0.7
3		Seom River	1001330	55.4	56.1	-0.7	1.3
4		Cheongmi Stream	1001630	25.2	25.3	-0.1	0.4
5		Bokha Stream	1002190	19.8	19.6	0.2	1.0
6		Bukhan River	1002710	158.8	166.9	-8.1	5.1
7		Yangguseo Stream	1002720	14.7	15.0	-0.3	2.0
8		Soyang River	1003000	77.3	74.3	3	3.9
9		Kyeongan Stream	1004290	22.5	199.9	2.6	11.6
10		Jungnang Stream	1005090	20.5	21.1	-0.6	2.9
11		Anyang Stream	1005380	20.7	20.7	0	0
12		Gongneung Stream	1005810	20.5	20.7	-0.2	1.0
13		Imjin River	1005980	91.1	90.5	0.6	0.7
14		Munsan Stream	1006760	11.6	13.8	-2.2	19.0
15	Nakdong River Basin	Nakdong River	2000010	383.0	391.1	-8.1	2.1
16		Banbyeon Stream	2000250	33.7	37.2	-3.5	10.4
17		Naeseong Stream	2000830	27.0	26.8	0.2	0.7
18		Gam Stream	2001550	39.0	41.8	-2.8	7.2
19		Geumho River	2001950	69.3	70.3	-1.0	1.4
20		Hwang River	2002860	78.8	83.6	-4.8	6.1
21		Nam River	2004040	144.6	143.1	1.5	1.0
22		Deokcheon River	2005160	4.2	5.0	-0.8	19.0
23		Haman Stream	2006110	9.6	9.9	-0.3	3.1
24		Milyang River	2006950	31.5	31.3	0.2	0.6
25		Yangsan Stream	2007500	10.1	10.5	-0.4	4.5
26	Geum River Basin	Geum River	3000010	360.7	353.1	7.6	2.1
27		Gap Stream	3001490	33.5	33.9	-0.4	1.1
28		Yudeung Stream	3001620	15.5	15.5	0.0	0.0
29		Miho Stream	3001810	39.1	39.6	-0.5	1.2
30		Nonsan Stream	3003970	21.5	23.0	-1.5	7.2
31		Ganggyeong Stream	3004230	6.4	6.7	-0.3	4.5

Table 6 (Continued)**.** Comparison Results of the Stream Length of the KRF Graphic Data and the Korean River List

No.	Basin Name	River Name	Standard Stream Code	Length in Korean River List (A) [km]	Length in Korean Reach File (B) [km]	Length Differences (A-B) [km]	Absolute Percentage Error |A-B|/A*100 [%]
32	Yeongsan/ Seomjin River Basin	Seomjin River	4000010	173.3	173.9	-0.6	0.3
33		Yo Stream	4001000	17.9	17.8	0.1	0.6
34		Boseong River	4001390	46.8	44.4	2.4	5.1
35		Yoengsan River	5000010	111.7	117.4	-5.7	5.1
36		Hwangryong River	5000300	9.4	9.5	-0.1	1.0
37		Jiseok Stream	5000600	34.0	33.8	0.2	0.6
38		Gomakwon Stream	5001220	22.4	23.9	-1.5	6.8
39		Hampyeong Stream	5001350	13.9	14.2	-0.3	2.1
						MAPE	3.8%

watershed that affect the end or junction of rivers must be controlled when the concentration of Biochemical Oxygen Demand (BOD) or Total Phosphorus (T-P) exceeds the preset permissible level (MOE, 2004). Under these parameters, it is difficult to easily search for stream reaches that are directly affected by individual pollution sources without the KRF. In the past, visual assessment using a paper map was the only way to identify pollution sources. The limitation of that system is that it does not minimize the expansion and diffusion of water pollution through prompt action. Furthermore, it is impossible to clearly define stream reaches that are affected by individual pollution sources and this can lead to legal disputes over the responsibility among municipalities.

We expect that the KRF will be used as an efficient scientific tool to provide a solution for the problem mentioned above. The KRF's unique identifiers can be used as the spatial addresses on stream networks (Lee et al., 2014). Once a unique identifier of the relevant stream reach adjacent to the discharge site of individual pollution sources is identified, it can be linked to individual records of existing pollution source databases. This will provide a list of pollution sources linked to the target stream reach within a short period of time, thereby enhancing the capabilities of mitigation strategies. The KRF also enables a network analysis for path finding, since it contains topology information of stream reaches connected upstream. It is possible to search for every relevant pollution source by exploring stream reaches in the upstream direction through a network analysis. This will support an analysis of discharge records of the sought pollution sources to find a cause and establish BMPs.

Figure 10a displays an example of pollution source information linkage and search using the KRF. The region shown in this figure is Kyeongan Stream's watershed, one of the twenty-four watersheds in the Han River basin. As shown on the left side, there are nine sewage treatment plants and ten water quality measurement sites. In this case, on the assumption that the concentration of BOD at the fifth water quality measurement site from the bottom exceeds the permissible level, the list of pollution sources affecting the site can be searched for through network analysis and database search using the KRF, as shown in Figure 10.b. First, it is necessary to choose a water quality measurement site and check a KRF Node ID for the site. In the example, the KRF Node ID value of the site is '1024290 11.95600'. The next step is to search for stream reaches adjacent to the node by finding the records that include the KRF Node ID value of the site at the <D_NODE_ID> field of the attributes table in the KRF's line. Two records which have <RCHLINID> as '1024290 11.95600 1' and '102429 11.95600 2' were found.

Next it is necessary to repeatedly search for stream reaches connected to the upstream area from those reaches. The unique identifier of the stream reaches in the left upstream direction '1024290 22.80969 2' can be created by combining the attributes in the fields of <ULSEG>, <ULMI> and <ULTRIB> of the first record. Then, the newly created unique identifier can be used to search for the record that has the same value in the field of <RCHLINEID>. As shown in Figure 10b, the third record with an attribute of <RCHLINEID> as '1024290 22.80969 2'can be found. Searching for stream reaches connected to the upstream area must be repeated until there are no more stream reaches connected to the upstream area. Likewise, the stream reaches in the right upstream direction must be searched for repeatedly using the attributes in the fields of <URSEG>, <URMI> and <URTRIB>.

Finally, the list of stream reaches extracted from the repeated search process can be used to find pollution sources. In this example, forty-six stream reaches and four sewage treatment plants relevant to them were found, as shown in Figure 10b.

The search results can also be used for mapping in GIS

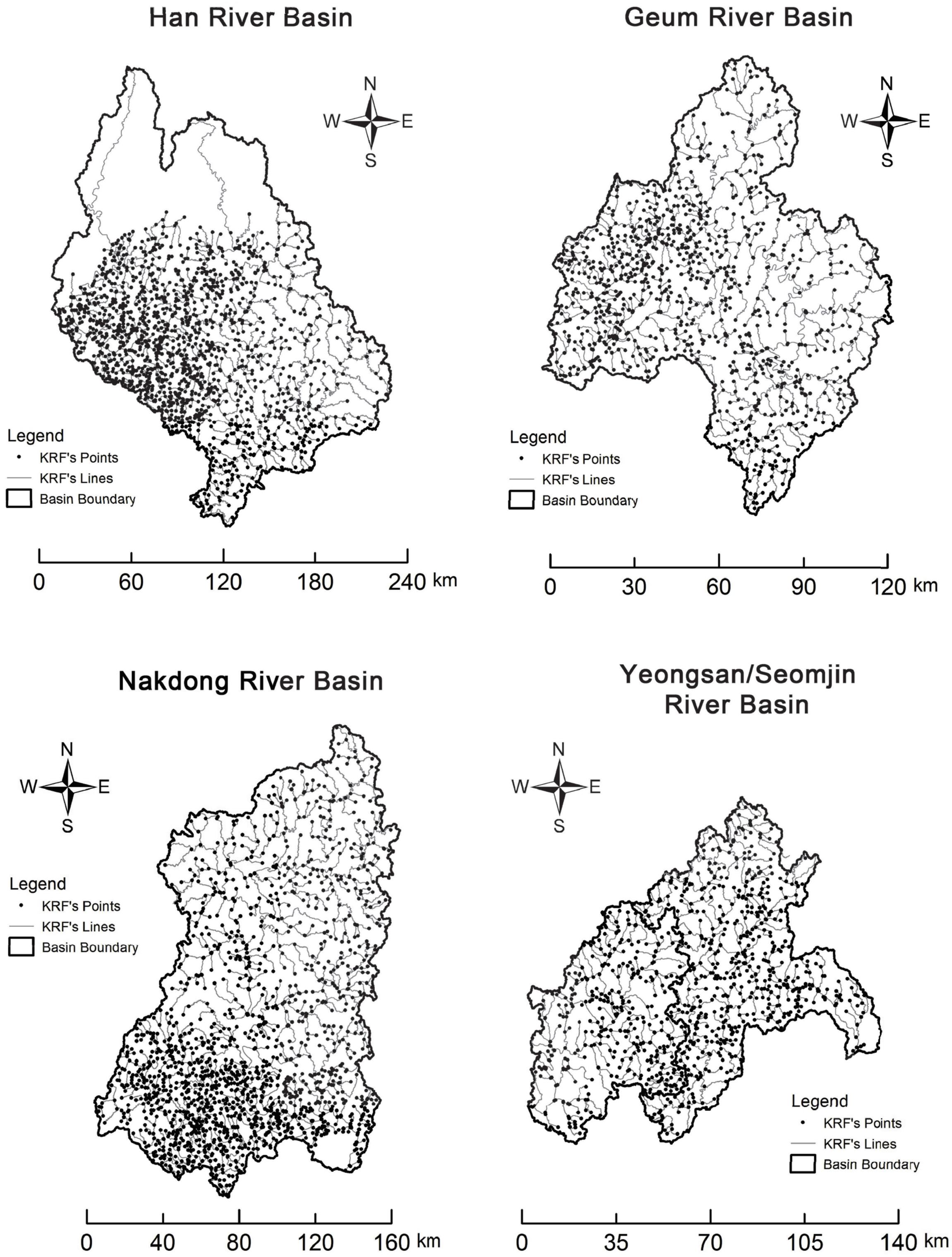
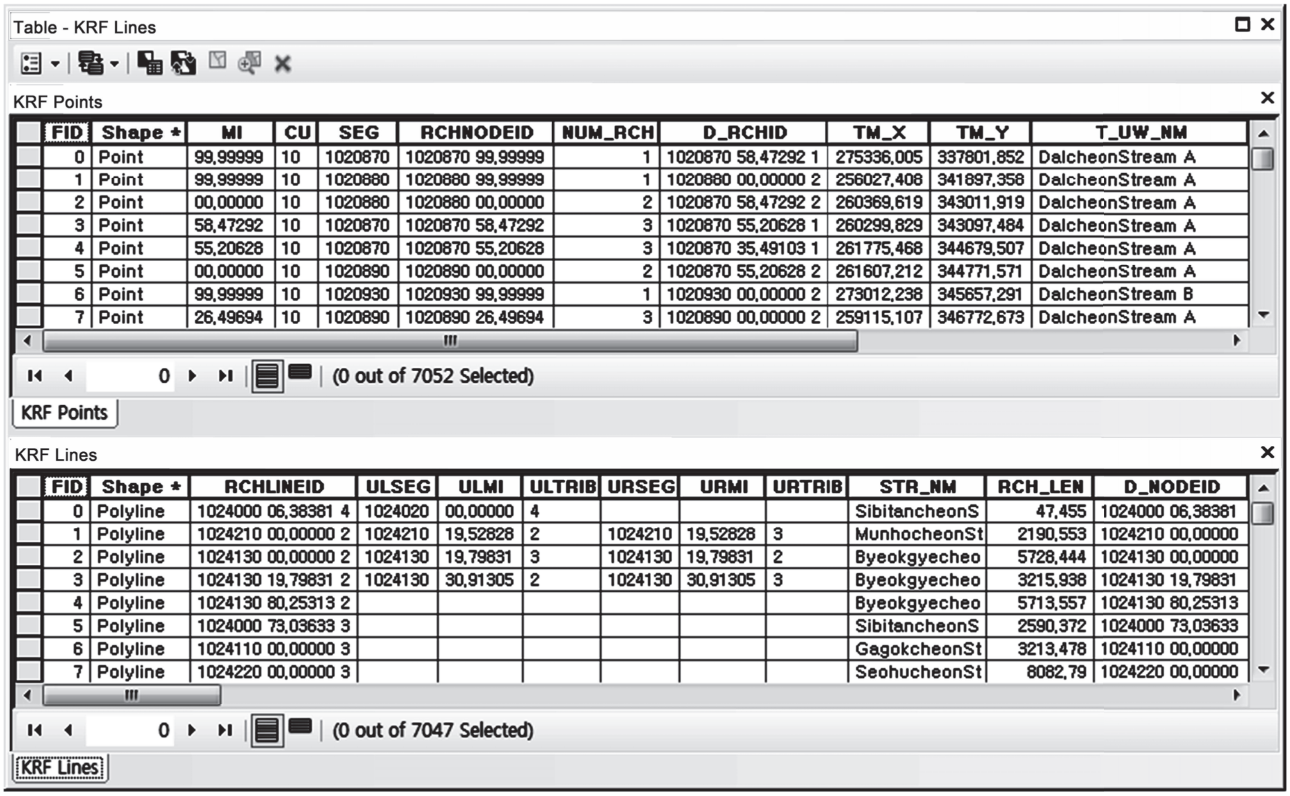


Figure 7. Results of generated KRF's graphic data of four major river basins.



FID	Shape *	MI	CU	SEG	RCHNODEID	NUM_RCH	D_RCHID	TM_X	TM_Y	T_UW_NM
0	Point	99,99999	10	1020870	1020870 99,99999	1	1020870 58,47292 1	275336,005	337801,852	DalcheonStream A
1	Point	99,99999	10	1020880	1020880 99,99999	1	1020880 00,00000 2	256027,408	341897,358	DalcheonStream A
2	Point	00,00000	10	1020880	1020880 00,00000	2	1020870 58,47292 2	260369,619	343011,919	DalcheonStream A
3	Point	58,47292	10	1020870	1020870 58,47292	3	1020870 55,20628 1	260299,829	343097,484	DalcheonStream A
4	Point	55,20628	10	1020870	1020870 55,20628	3	1020870 35,49103 1	261775,468	344679,507	DalcheonStream A
5	Point	00,00000	10	1020890	1020890 00,00000	2	1020870 55,20628 2	261607,212	344771,571	DalcheonStream A
6	Point	99,99999	10	1020930	1020930 99,99999	1	1020930 00,00000 2	273012,238	345657,291	DalcheonStream B
7	Point	26,49694	10	1020890	1020890 26,49694	3	1020890 00,00000 2	259115,107	346772,673	DalcheonStream A

FID	Shape *	RCHLINEID	ULSEG	ULMI	ULTRIB	URSEG	URMI	URTRIB	STR_NM	RCH_LEN	D_NODEID
0	Polyline	1024000 06,38381 4	1024020	00,00000	4				SibitancheonS	47,455	1024000 06,38381
1	Polyline	1024210 00,00000 2	1024210	19,52828	2	1024210	19,52828	3	MunhocheonSt	2190,553	1024210 00,00000
2	Polyline	1024130 00,00000 2	1024130	19,79831	3	1024130	19,79831	2	Byeokgyecheo	5728,444	1024130 00,00000
3	Polyline	1024130 19,79831 2	1024130	30,91305	2	1024130	30,91305	3	Byeokgyecheo	3215,938	1024130 19,79831
4	Polyline	1024130 80,25313 2							Byeokgyecheo	5713,557	1024130 80,25313
5	Polyline	1024000 73,03633 3							SibitancheonS	2590,372	1024000 73,03633
6	Polyline	1024110 00,00000 3							GagokcheonSt	3213,478	1024110 00,00000
7	Polyline	1024220 00,00000 3							SeohucheonSt	8082,79	1024220 00,00000

Figure 9. Results of the KRF's attribute table.

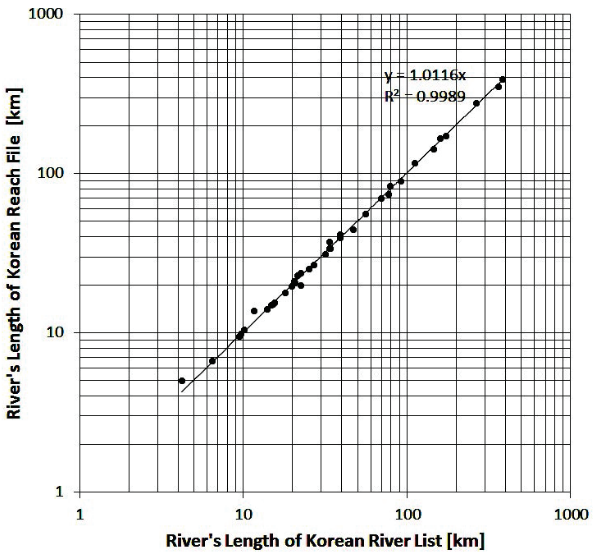


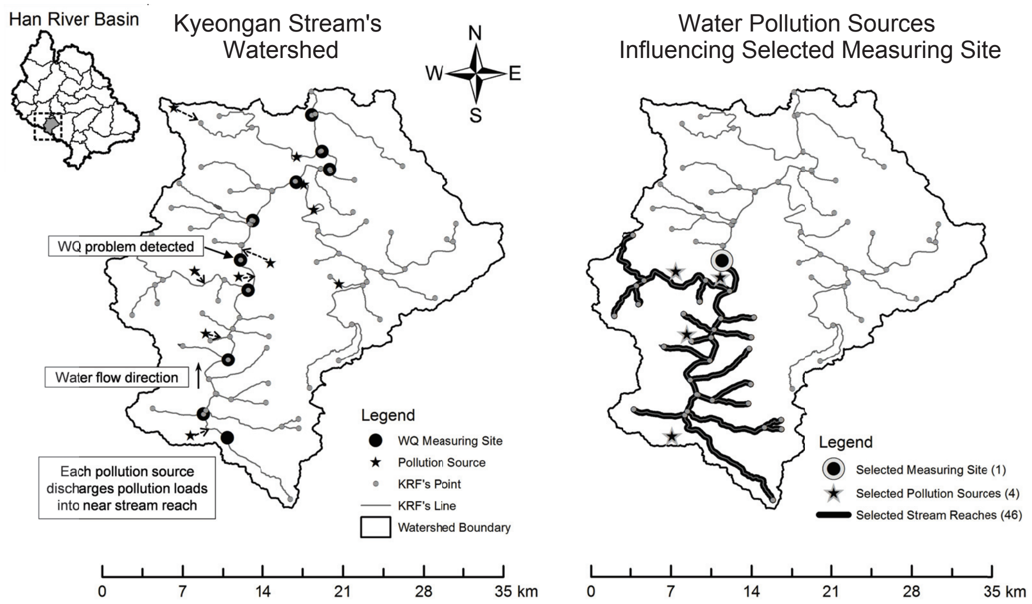
Figure 8. Scatter plot for comparison of national rivers' lengths.

environment, as shown in the right side of Figure 10a. This can be a significant contribution to establish more realistic BMPs considering spatial distribution and correlation among spatially distributed relevant factors. It is also possible to easily predict and identify stream sections that might be influenced by water pollutants in the future by applying this method in the downstream direction. In particular, this can be applied in a similar way by entering KRF's unique identifiers in various databases related to facilities such as intake stations, purification plants and leisure facilities (swimming pools, fishing sites, etc.). This application will support more efficient decision-making to analyze water pollution scenarios.

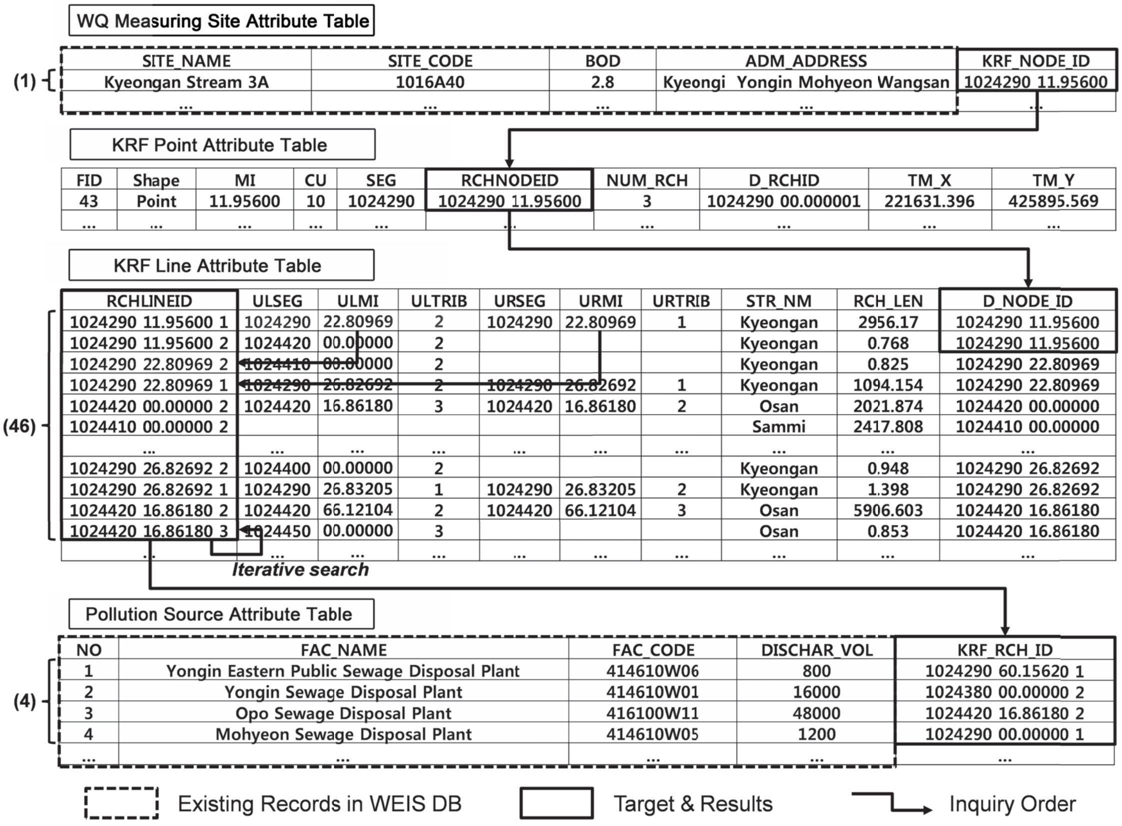
The scientific assessment of discharge permission and the management of diverse pollution sources through prediction of water quality changes in TMDLs require a GIS based water quality simulation and assessment support system such as the U.S. EPA's BASINS (USEPA, 2001). Such a system will support diverse use of models related to water quality with the linkage of the KRF attributes. The KRF attributes contain basic information required for creating a model schematic diagram like the length of stream reaches (in the field of <RCH_LEN>), the Boolean variable of uppermost stream reaches (in the field of <S_FLAG>), the Boolean variable of lowest stream reaches (in the field of <T_FLAG>), the Boolean variable of stream reach connection (in the field of <R_FLAG>), and so on. Therefore, the KRF can be used effectively in preprocessing topographical data and creating model input data for water quality simulation (Park et al., 2013) once the GIS based modeling system has been developed.

6. Conclusions

In this study, the GIS based KRF was generated for the four major river basins in South Korea as the stream network data to support TMDLs implementation. The method's effec-



(a) Application to search pollution sources for TMDLs (Left: a scenario, Right: a search result)



WQ Measuring Site Attribute Table

SITE_NAME	SITE_CODE	BOD	ADM_ADDRESS	KRF_NODE_ID
Kyeongan Stream 3A	1016A40	2.8	Kyeongi Yongin Mohyeon Wangsan	1024290 11.95600
...	...	...	...	...

KRF Point Attribute Table

FID	Shape	MI	CU	SEG	RCHNODEID	NUM_RCH	D_RCHID	TM_X	TM_Y
43	Point	11.95600	10	1024290	1024290 11.95600	3	1024290 00.000001	221631.396	425895.569
...	...	...	...	...	...	...	...	...	...

KRF Line Attribute Table

RCHLINEID	ULSEG	ULMI	ULTRIB	URSEG	URMI	URTRIB	STR_NM	RCH_LEN	D_NODE_ID
1024290 11.95600 1	1024290	22.80969	2	1024290	22.80969	1	Kyeongan	2956.17	1024290 11.95600
1024290 11.95600 2	1024420	00.00000	2				Kyeongan	0.768	1024290 11.95600
1024290 22.80969 2	1024410	00.00000	2				Kyeongan	0.825	1024290 22.80969
1024290 22.80969 1	1024290	26.82692	2	1024290	26.82692	1	Kyeongan	1094.154	1024290 22.80969
1024420 00.00000 2	1024420	16.86180	3	1024420	16.86180	2	Osan	2021.874	1024420 00.00000
1024410 00.00000 2							Sammi	2417.808	1024410 00.00000
...	...	...	...	...	...	...	...	...	...
1024290 26.82692 2	1024400	00.00000	2				Kyeongan	0.948	1024290 26.82692
1024290 26.82692 1	1024290	26.83205	1	1024290	26.83205	2	Kyeongan	1.398	1024290 26.82692
1024420 16.86180 2	1024420	66.12104	2	1024420	66.12104	3	Osan	5906.603	1024420 16.86180
1024420 16.86180 3	1024450	00.00000	3				Osan	0.853	1024420 16.86180
...	...	...	...	...	...	...	...	...	...

Pollution Source Attribute Table

NO	FAC_NAME	FAC_CODE	DISCHAR_VOL	KRF_RCH_ID
1	Yongin Eastern Public Sewage Disposal Plant	414610W06	800	1024290 60.15620 1
2	Yongin Sewage Disposal Plant	414610W01	16000	1024380 00.00000 2
3	Opo Sewage Disposal Plant	416100W11	48000	1024420 16.86180 2
4	Mohyeon Sewage Disposal Plant	414610W05	1200	1024290 00.00000 1
...	...	...	...	...

(b) Search process of the pollution source data using the KRF

Figure 10. Application example of the KRF for TMDLs.

tiveness and accuracy were evaluated. In addition, future application and utilization plans for the KRF were discussed.

The previous studies of the U.S. and South Korea were investigated to define an appropriate methodology to generate the KRF. To produce line type graphic data required for the generation of network spatial data, the skeletonizing method connecting center points from maximum inscribed circles was applied. Adopting the skeletonizing method and post-processing, the stream flow line was delineated from a vector type river/stream map. In addition, with the application of the stream reach split standard defined in this study, the line type graphic data of a stream reach unit can be produced. The point type graphic data were produced through the screen digitizing at the start and end points of individual stream reaches. The unique identifier was developed using Korean standard stream code and all stream reaches and nodes could be identified. Finally, themes, location and topology attributes were entered for all the stream reaches according to the attribute design.

A total of 7,047 stream reaches were delineated for 2,402 rivers and streams, and their total length was 21,163.27 km. As the result of comparing with Korean River List--the actual surveyed data of major national rivers--the MAPE was found to be about 3.8%; an acceptable level of accuracy for the proposed method. The KRF and relevant network data can surely contribute to enhancing the network analysis in TMDLs implementation. The unique identifier and several theme attributes can be utilized for data connection with various existing stream databases of environment information. Furthermore, the topology attributes could be used for more effective network analysis. The study results also suggest that further research is needed to validate the efficiency and usefulness of the KRF with more efforts to develop various application systems to utilize the KRF in TMDLs work.

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