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Article

Estimation of Temperature Recovery Distance and the Influence of Heat Pump Discharge on Fluvial Ecosystems

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Abstract: Temperature differences between the atmosphere and river water allow rivers to be used as a hydrothermal energy source. The river-water heat pump system is a relatively non-invasive renewable energy source; however, effluent discharged from the heat pump can cause downstream temperature changes which may impact sensitive fluvial ecosystems. In this study, the water temperature recovery distance of the effluent was estimated for a river section in the Han River Basin, Korea, using the heat transfer equation and the Environmental Fluid Dynamic Code (EFDC) model. Results showed that, compared to the EFDC model, the heat transfer equation tended to overestimate the water temperature recovery distance due to its simplified assumptions. The water temperature recovery distance could also be used as an objective indicator to decide the reuse of downstream river water. Furthermore, as the river system was found to support an endangered fish species that is sensitive to water environment changes, care should be taken to exclude the habitats of protected species affected by water temperatures within water temperature recovery distance.

Keywords: hydrothermal energy; river-water heat pump; water temperature recovery distance; heat transfer equation; Environmental Fluid Dynamic Code (EFDC); Han river basin

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1. Introduction

River-water temperature is an important water quality factor. On the other hand, water temperature changes play a significant impact on the river environment. This is shown when the community structures of fish and benthic macroinvertebrates are altered by water temperature changes [1]. For example, rising water temperatures narrow the habitation range of cold-water organisms and rapidly increases the growth of specific hot water fish species, altering the ecosystem balance and distribution of aquatic organisms [2]. Extensive research has focused on the effects of water temperature on the river environment [3,4].

The use of river water as a heat pump is considered a source of an environment-friendly renewable energy. The river-water heat pump system is an air-conditioning system that uses energy derived from the temperature difference between river water and the air. However, when using river water as a hydrothermal energy source, the discharge water temperature differs from the intake; thus, the water discharged in the cooling process increases the water temperature, while the effluent in the heating process lowers it. This temperature change impacts both the discharge site and the downstream section. Therefore, when using the river water hydrothermal energy, it is necessary to verify the extent of water temperature changes and their environmental impact on the downstream ecosystem.

River-water temperature is influenced by atmospheric conditions, including air temperature, solar radiation, relative humidity, cloud cover, and wind speed [5], which are related to heat

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exchange between the air and river [6]. Edinger et al. [7,8] were among the first to conduct comprehensive research on this air–water heat transfer and defined the concept of equilibrium temperature. They also investigated the discharge temperature half-life from a hydroelectric power plant. Thomann and Mueller [9] and Chapra [10] presented a theoretical method to determine the correlation between thermal energy and water temperature. Furthermore, Sinokrot and Stefan [11,12] modeled river-water temperatures to examine fish habitats under climate change and developed a numerical model to calculate hourly river temperatures using a one-dimensional advection-diffusion heat exchange equation and the finite difference method. Finally, Prats et al. [13] investigated the effects of heat flux on the Ebro River in Spain and defined the recovery distance as the distance at which the temperature difference falls below 0.5 ℃ following the discharge of hot water.

The Korea Ministry of Science and Technology [14] analyzed the distance from the upstream entry point to the equilibrium temperature and determined that rivers with a high flow rate recovered to the equilibrium temperature within 10 km, while low flow rate rivers recovered within 1–4 km. Seo et al. [6] developed a horizontal two-dimensional finite element model to analyze the mixing behavior of heat pollutants, and compared the derived numerical solution with the solution determined using the heat transfer equation. Furthermore, Lee et al. [15] predicted the dispersion range of cool water in a Liquefied Natural Gas(LNG) terminal using the Environmental Fluid Dynamic Code(EFDC) model. Although various studies have investigated the behavior of water temperatures in rivers, there is few which have examined the environmental impact of river-water heat pump discharge. Furthermore, in previous studies on the range of river water temperature, they measured changes in water temperature by river section or used a one-dimensional transfer equation. As the demand for river water heat pump systems is expected to increase steadily, it is necessary to objectively analyze the environmental impact of river-water temperature changes considering the characteristics of the river environment. Therefore, in this study, we investigate changes in river water temperature according to the distance from the effluent discharge point to determine the 'water temperature recovery distance' using the heat transfer equation and the three-dimensional hydraulic and water quality model, EFDC.

2. Methods

2.1. Summary of hydrothermal energy

Hydrothermal energy can be derived from any water source that has a temperature differential with the air; for example, wastewater, river water, lakes, groundwater, and sea water [16,17]. Generally, hydrothermal resources have a lower than air temperature in summer and a higher than air temperature in winter and are mainly used for cooling and heating [18–20].

A river-water heat pump system can concentrate heat by compressing refrigerant gases and then transfer this heat into buildings to provide warmth through heat exchangers. Refrigerant gases cool when the pressure is released and can be exchanged with warmer water from the river. In this way, river water is transported to the heat exchanger, and cooled water is discharged into the river in winter. The river is warmer than the air during winter, so a water-source heat pump is more efficient than a pump using air. The reverse is true during summer, when cool river water is transported to the heat exchanger, and the heated river water is discharged [21].

2.2. Estimation of water temperature recovery distance

The 'water temperature recovery distance' is the distance from the discharge point to the point at which the river water temperature becomes the original temperature of the river. There are two ways to determine the influence of effluent on a river system. This involves simulations using hydraulic and hydrologic model or calculation of water temperature distribution using material balance equation [22]. In this study, the water temperature recovery distance was estimated by using a heat transfer equation and the EFDC model.

2.2.1. Heat transfer equation

A heat transfer equation describing the correlation between river-water temperature and air temperature was used in this study. The water temperature recovery distance was calculated by applying the material balance equation from Edinger et al. [7] and Hwang [23] as follows :

$$T = (T_0 - T_b)\exp\left(-k\frac{x}{u}\right) + T_b \ [°C],\ k = \frac{K_e}{\rho_w C_w h}\ [s^{-1}],$$

$$x = \frac{u}{k} ln\left|\frac{20}{3}(T_0 - T_b)\right| = \frac{\rho_w C_w h u}{K_e} ln\left|\frac{20}{3}(T_0 - T_b)\right|\ [\text{m}],\ |(T_0 - T_b)| \le 0.15°C, \quad (1)$$

where T(°C) is the water temperature after the distance x, T_b(°C) is the water temperature at the upstream, T_0 is the water temperature after the discharge becomes fully mixed with the river water(°C), x is the water temperature recovery distance which is distance until T_0 becomes T_b(m), k is the total heat exchange coefficient(s^{-1}), K_e is the surface heat exchange coefficient(W/m^2· °C), ρ_w is the water density(998.2 kg/m^3), C_w is the specific heat of water(4,186 J/kg· °C), h is the mean river depth(m), and u is the water velocity(m/s).

The boundary condition at the effluent entry point is $T = T_0$, where T_0 is the temperature after the river water is mixed with effluent water. Prats et al. [13] estimated the water temperature recovery distance as the distance that makes the difference between the mean daily water temperature and mean daily steady state water temperature <0.5 °C. In this study, the water temperature recovery distance was calculated from equation (1). This is in accordance to the assumption that the water temperature recovery distance is the distance at which the difference between the river water temperature and the water temperature discharged from heat pump is less than 0.15 °C, as modified by Prats et al. [13]. Due to lack of research background on the river, the criteria used are based on the objective judgments of the researchers.

In order to estimate the temperature recovery distance, the surface heat exchange coefficient K_e should be estimated first. It can be estimated through the equation (2) suggested by Edinger et al. [7]:

$$K_e = 4.48 + 0.05T_s + \beta f(W) + 0.47 f(W), \quad (2)$$

$$\beta = 0.35 + 0.015T_m + 0.0012T_m^2\ [mmHg/°C],\ T_m = \frac{T_s + T_d}{2} \quad (3)$$

$$f(W) = 9.2 + 0.46W^2\ [W/m^2 \cdot mmHg], \quad (4)$$

where T_s is surface water temperature, β is the slope between two points on the saturated vapor pressure curve, $f(W)$ is wind speed function, T_d is dew point temperature, and W is wind speed at 7m above the water surface.

2.2.2. The EFDC model

The EFDC, which is non-commercial model, is a multifunctional surface-water modeling system which includes hydrodynamic, sediment-contaminant, and eutrophication components [24]. The EFDC model can integrate simulations of density currents (such as water quality), suspended sediments, and saltwater with hydraulic simulations of structures in the water, wet/dry simulations, and material tracking in a three-dimensional hydrodynamic model. The EFDC model is considered to be suitable for the scenario analyzed in this study [25]. There are 5 options (No Atmospheric Linkage, Full Heat Balance Method, External Equilibrium Temperature Method, Constant Equilibrium Temperature Coefficient Method, and Equilibrium Temperature Method to simulate water temperature using EFDC model [26]. These configurations can be set in the card image six (C6) of the EFDC.INP file, which is the main input file for EFDC. In this study, the Equilibrium Temperature Method(CE-QUAL-W2 Method) was used. It is because this method considers advection and diffusion, and calculates the water surface heat exchange rate based on the equilibrium temperature and heat exchange coefficient easily. The CE-QUAL-W2 model is a two-dimensional hydraulic and water quality model developed by the US Army Corps of Engineers. The equilibrium temperature method calculates the water surface heat exchange rate based on the equilibrium temperature and heat exchange coefficient as shown in equation (5) [27]:

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$$H_{aw} = -K_{aw}(T_w - T_e), \tag{5}$$

where H_{aw} is water-air heat exchange rate[W/m^2], K_{aw} is water-air heat exchange coefficient [$W/m^2 \cdot$ °C], T_w is water temperature[°C], T_e is equilibrium temperature[°C].

For topography data, a grid coordinate file was created using the Surface-water Modeling System(SMS) program, developed by Aquaveo, and the topography information file was used in the EFDC Explorer5 to create the model [28].

2.3. Area of Study

For a river system to be viable for hydrothermal energy utilization, the stability of the river flow must be considered. Jung et al. [29] identified rivers in Korea with sufficient water flow for hydrothermal applications. To examine possible intake areas, the permissible reference flow rate was calculated and sections of river that exceeded the reference flow rate were examined using geographic information system analysis to determine whether buildings that could benefit from hydrothermal heating and/or cooling were within 1 km of the river. With reference to the results of Jung et al. [29] and based on the ease of data acquisition, the river reach from the Yangpyeong Stage Gauge to the Lower Namhan River Watershed of the Han River mainstream in the central Lower Namhan River Watershed was selected for analysis in this study. This section of the Lower Namhan River Watershed has a channel length of 60.81 km and a watershed area of 2,072.72 km^2, accounting for 6.02% of the Han River Basin. The average watershed width is 34.1 km, and the watershed shape factor is 1.18. The watershed area of Yangpyeong water stage gauging station and Lower Namhan River Watershed are 128.9 km^2 and 88.5 km^2. The main channel length is 25.6 km, and coefficient of roughness is 0.03. Time of concentration is 2.8 hr, curve number is 78.7, and mean elevation of basin is 437.8 EL.m.

2.4. Data collection and analysis

In the analysis, the weather and level stations are shown in Tables 1 and 2, respectively. The EFDC model requires weather, water level, and flow data for boundary locations. Thus, data were collected from the boundary locations at Ipo Weir, Cheongpyeong Dam, and Paldang Dam.

To account for the impact of the Ipo Weir, water temperature observation data from January 1 to December 31, 2017, following the weir's construction, were used. The annual average air temperature at the Yangpyeong weather station was 12.30 ℃ and temperature shows a clear seasonality (Figure 2, grey dotted line). We assume that river water was used for cooling in summer and heating in winter, and summer and winter were considered to be June–August and December–February, respectively. The summer (winter) average air temperature was 24.88 ℃(–1.82 ℃).

When flow rates at the Yangpyeong-gun (Yangpyeong Bridge) level station were examined, flow was high during the summer flood season and low during winter. In 2014 and 2015, flow rates were low even in the summer due to drought. The average flow rate of Yangpyeong-gun (Yangpyeong Bridge) was 366.7 m^3/s in summer and 126.9 m^3/s in winter. Summer flow is approximately three times higher than the winter flow (Figure 3).

To account for conditions under which water discharge has the maximum effect, the water temperature recovery distance was estimated using the minimum flow rate during the observation period. Daily and hourly water temperatures were collected from the Yanpyeong, Hongcheon, and Gapyeong water quality stations, which belong to the automated water quality monitoring network of the Water Environment Information System. The Yangpyeong water quality station, which is the closest to the intake and discharge points, was installed in December 2014, and has a data record from April 2015. The annual, summer, and winter average water temperatures were 16.3, 26.3, and 3.7 °C, respectively. Figure 4 compares Yangpyeong water quality station data with the nearby Gangsang water quality monitoring network, which only measures three to four times a month.

3. Results and Discussion

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3.1. Heat transfer equation method

Table 3 lists the input data required to estimate the water temperature recovery distance using the heat transfer equation. In order to consider the worst condition that the maximum temperature recovery distance can be calculated, the following values were used as constants. The average values for each season were used for water temperature, depth, and flow velocity. For the flow rate and surface heat exchange coefficient, the minimum value for each season was used.

The discharge water temperature was set to 7 °C higher than the river-water temperature during summer and 5 °C lower during winter. The input and discharge rate was set to 0.64 m^3/s. We assume that discharge water flows into the existing river and is completely mixed, and no other weather or environmental changes occur. Furthermore, we assume that water depth, flow velocity, and wind speed are constant.

The mixed water temperature immediately after entry, T_0, was set to the weighted average value of the river flow and discharge. Table 4 shows seasonal river-water temperature, discharge water temperature, and mixed water temperature immediately after entry. In summer, the mixed water temperature immediately after entry was 0.16 °C higher than the existing river-water temperature, and 0.18 °C lower in winter. Table 5 shows the calculated water temperature recovery distance.

3.2. EFDC model

The model grids for simulating the water temperature recovery distance were composed of 89 lateral grids, 234 longitudinal grids, 1,484 horizontal segments, and 10 layers in the water column, resulting in a total of 14,840 unit grids. Furthermore, to simulate the target river section in more detail, a model of the target river reach was constructed with 19 grids in the lateral direction (approximately 47.5 m per interval), 310 grids (approximately 75 m per interval) in the longitudinal direction, and 2,676 segments in the horizontal direction.

The initial boundary conditions of the water layer were derived from the date of the lowest flow rate in each season during the observation period, including sea-level pressure, air temperature, relative humidity, precipitation, solar radiation, inflow rate, water level, water temperature, wind speed, and wind direction (Tables 6 and 7).

The result of the water temperature is compared to the observed water temperature at Yangpyeong water quality station. As a result, the average simulated water temperature in summer was 24.3 ℃, which was about 0.3 ℃ different from the actual observed water temperature of 24.0 ℃. The average simulated water temperature in winter was 1.4 ℃, which was about 0.1 ℃ different from the actual observed water temperature of 1.5 ℃. From these results, we concluded that the EFDC model is properly constructed.

The discharge water temperature from heat pump and its range of influence were calculated while performing water intake and discharge at 0.64m^3/s. We used the Yangpyeong automated water quality monitoring network site as the discharge location, approximately 250 m downstream from the intake site. Discharge water temperature was 31.0 °C during summer and –3.8 °C during winter, which was 7 °C higher and 5 °C lower, respectively than the input water.

Immediately after discharge (at i = 156, j = 9; grid no. 2) the water temperature was estimated through vertical grid simulation results for the same lateral number (i = 156) and longitudinal number(j = 9) as those of the discharge site. The simulation period was set to 3 months in both summer and winter, but the front part of the model should be removed for the stability of the model. A summer recovery distance simulated on August 1(123 days) with no intake and discharge was used as the reference value. Then, the longitudinal, lateral, and vertical water temperature recovery distances from the discharge site were estimated(Figure 5). The summer recovery distance was approximately 4.5 km downstream and 0.5 km upstream(Figure 6). Discharge water impacted the entire river width (300 m) to a depth of approximately 1 m(in 5 m of water).

The winter water temperature recovery distance was calculated in the same way as for the summer. The water temperature recovery distance was simulated on January 31(123 days). The

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winter recovery distance was approximately 6.7 km(6.1 km downstream and 0.6 km upstream; Figure 6) with a lateral influence of approximately 120 m. The river was impacted to a depth of 3.5 m.

3.3. Comparison of methods

Table 9 summarizes the water temperature recovery distances estimated using the heat transfer equation and the three-dimensional EFDC models. The water temperature recovery distances estimated by the heat transfer equation and the EFDC model were 9.7 and 5 km, respectively, in summer and 4.5 and 6.7 km, respectively, in winter. The three-dimensional temperature recovery distance of the EFDC model shows that during summer, the longitudinal distance is shorter than the result obtained from the heat transfer equation but wider in the lateral direction during winter. On the other hand, the longitudinal distance during winter was estimated to be longer than the result of the heat transfer equation while its lateral distance is relatively short. These differences can be attributed to the fact that the heat transfer equation can be simulated in the flow direction only, and thus it does not account for potential upstream effects. Furthermore, the heat transfer equation model makes a number of assumptions such as complete and instantaneous mixing, which do not reflect the actual conditions in the stream flow. More precise quantitative analysis is possible in the EFDC model, particularly the three-dimensional model, and as such, the recovery distances estimated using this method are more likely to be representative of actual river conditions. However, in this study, there is a limit to estimating the volume of the stream that actually affects it as temperature recovery distance was estimated using only the longitudinal, lateral and vertical directions at the effluent discharge point.

3.4. Environmental impact of river-water temperature changes

Our results indicate that river water hydrothermal installations will impact river-water temperatures at least about 4.5 km downstream of effluent discharge and up to a distance of about 9.7 km. Hence, it is important to consider their impact on species vulnerable to water temperature changes within the water temperature recovery distance. In particular, attention should be given to the existence or absence of habitats for endangered animals within the water temperature recovery distance. Endangered wildlife refers to a species that is determined by the Korean Minister of Environment as a wildlife that may be endangered in the near future if the population is greatly reduced due to natural or artificial threats or if the current threat is not removed or mitigated [30]. Twenty-five species of fish are currently designated among endangered wildlife in Korea [22]. Figure 7 outlines the status of endangered animals that inhabit river sections that are viable for hydrothermal applications. It is apparent that Acheilognathus signifer inhabits the Yangpyeong Stage Gauge within the target river section analyzed in this study. Acheilognathus signifier is a freshwater fish species indigenous to the Korean Peninsula. The species is highly sensitive to the water environment and populations are declining rapidly because the habitats of their spawning host clams have been disturbed. Acheilognathus signifier fertilization and hatching occurs at approximately 22 ℃ and the maximum immunity temperature for the species is 28 ℃. Therefore, it is possible that heat pump discharge during the summer could impact Acheilognathus signifier habitats. Consequently, potential hydrothermal installations should assume a summer water temperature recovery distance of 9.73 km in the target river reach and plan effluent discharge to avoid impacting water temperatures at the Yangpyeong Stage Gauge observation site.

4. Conclusions

River-water temperature changes caused by discharge from hydrothermal heat pumps were investigated to examine the environmental feasibility of river water hydrothermal energy applications in ecologically sensitive areas. A location was selected in the Han River Basin based on a previous study that examined the stability of flow rates for river water heat sources. Changes in water temperature were considered in terms of the water temperature recovery distance; the distance at which the impact of the hydrothermal effluent on river-water temperature was reduced to less

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than 0.15 ℃. Two methods of determining the water temperature recovery distance were used in this study; the heat transfer equation method and the EFDC three-dimensional model.

Discharge water was assumed to be 7 ℃ higher than the existing river-water temperature in summer and 5 ℃ lower in winter. The summer water temperature recovery distance was estimated to be 9.7 km using the heat transfer equation method and 5 km using the EFDC model. In winter, the water temperature recovery distance was estimated to be 4.5 km using the heat transfer equation method and 6.7 km using the EFDC model. The heat transfer equation is less reliable, because there are many assumptions such as full mixing at same time. The EFDC model shows that the temperature change between the top and bottom can be simulated more accurately by dividing the water layer in the depth direction.

The environmental conditions used in this study were chosen to ensure that the simulated discharge water would have the greatest impact on the river environment. Therefore, it is likely that the simulated water temperature recovery distance may overstate the actual water temperature recovery distance. Notwithstanding, a water temperature recovery distance of 9.7 km suggests that the discharge from a river-water heat pump has no environmental impact beyond 9.7 km from the effluent discharge point. This measure could also be used as an objective indicator for the reuse of downstream river water, and the repeat installation of river-water heat pumps.

When endangered species in the vicinity of the study location were examined, an endangered fish species (Acheilognathus signifer) that is sensitive to water environment changes was found to inhabit some sections. Therefore, care should be taken to exclude the habitats of Acheilognathus signifer and other protected species affected by water temperatures up to 9.7 km downstream of hydrothermal energy effluent discharge. If the environmental impact of these facilities is inevitable, then substitute habitats should be prepared for the protect species. This study was conducted to examine the environmental feasibility of the utilization of hydrothermal energy using river water source heat pump. Therefore, it is expected that the results of this study can be used as a baseline data for environmental feasibility reviews for hydrothermal energy utilization. This is also beneficial for preliminary consultation of interested parties including non-government organizations in countries where river water hydrothermal energy is lacking as well as interested residents in the downstream areas. In addition, it is expected that this study can be used to review the reuse of river water temperature in downstream areas especially in countries where river water hydrothermal energy is actively utilized.

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Table 1. Weather station (automated surface observation station) information.

Station code	Station name	Longitude (degree)	Latitude (degree)	Elevation above sea level (EL.m)	Observation start (year)	Observing system
114	Wonju	127.9	37.3	148.6	1971	ASOS[1]
202	Yangpyeong	127.5	37.5	48.0	1972	ASOS

[1] ASOS : Automated Surface Observing System.

Table 2. Level station information.

Station code	Station name	Longitude (degree)	Latitude (degree)	Zero elevation (EL.m)	Observation start (year)	Observing system
1007697	Yangpyeong-gun (Sinwon-ri)	127.4	37.5	24.3	2016	T/M[1]
1007685	Yangpyeong-gun (Yangpyeong Bridge)	127.5	37.5	19. 6	1953	T/M
1007660	Yeoju-si (Ipo Bridge)	127.3	37.4	26.1	2001	T/M
1015645	Gapyeong-gun (Daeseong-ri)	127.4	37.7	22.6	1914	T/M

[1] T/M : Tele-Metering.

Table 3. Input data for the heat transfer equation.

Season	Temperature T_b (°C)	Flow rate Q (m^3/s)	Depth h (m)	Velocity, u (m/s)	K_e ($W/m^2 \cdot °C$)
Annual average	16.3	203.3	5.7	0.105	18.0
Summer average	26.3	366.7	5.7	0.192	23.5
Winter average	3.7	126.9	5.7	0.006	13.1
Summer minimum	19.9	28.1	5.3	0.001	17.8
Winter minimum	1.0	16.7	5.2	0.001	11.8

Table 4. Seasonal river-water temperature, discharge water temperature, and mixed water temperature immediately after entry.

Division	River-water temperature, T_b (°C)	Discharge water temperature (°C)	Flow rate, Q (m^3/s)	Mixed water temperature immediately after entry, T_0 (°C)	Wind speed (m/s)	Change (°C)
Summer	26.3	33.3	28.1	26.4	1.4	▲0.16
Winter	3.7	−1.3	16.7	3.5	0.8	▼0.18

Table 5. Water temperature change and water temperature recovery distance results.

Distance	0.5 km	5 km	10 km	50 km	100 km	300 km	Water temperature recovery distance (km)
Summer (°C)	26.4	26.4	26.4	26.4	26.4	26.3	9.73
Winter (°C)	3.5	3.6	3.6	3.6	3.6	3.7	4.48

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Table 6. Weather input data by season.

Season	Sea-level pressure (mb)	Temperature (°C)	Relative humidity (%)	Precipitation (mm/h)	Solar radiation (W/m^2)
Summer (June 6, 2015)	1015.0	19.6	65.5	0.00	0.85
Winter (Dec. 20, 2015)	1032.2	−6.2	64.9	0.00	0.50

Table 7. Hydrologic and hydraulic input data by season.

Division	Inflow rate (m^3/s)	Exit level (m)	Influent water temperature (Hongcheon) (°C)	Wind speed (m/s)	Wind direction (10° intervals from true north)
Summer	43.3	25.2	22.6	1.4	110
Winter	16.7	25.3	2.4	0.8	200

Table 8. The validation results of EFDC.

Division	Average simulated water temperature (°C)	Observed water temperature (°C)	Median Error (°C)
Summer	24.3	24.0	0.17
Winter	1.4	1.5	

Table 9. Water temperature recovery distance estimation result by method.

Season	Heat transfer equation (km)	EFDC model (km)		
		Longitudinal direction	Lateral direction	Vertical direction
Summer	9.7	5.0	0.30	0.01
Winter	4.5	6.7	0.12	0.04

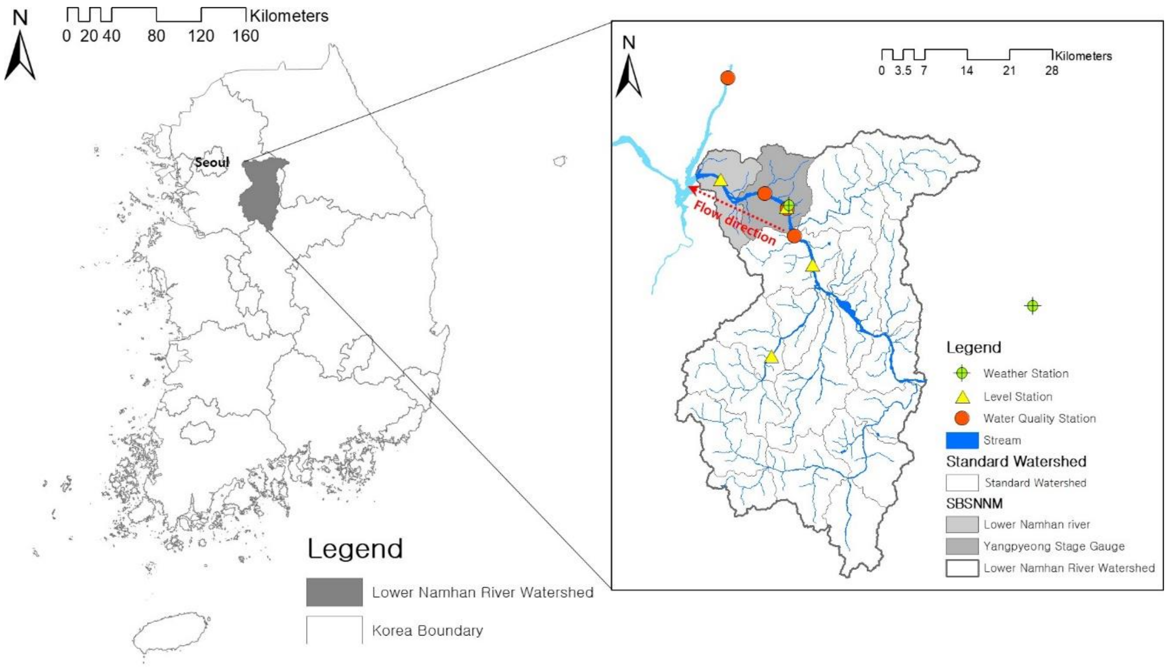

Figure 1. The lower Namhan River watershed, Korea.

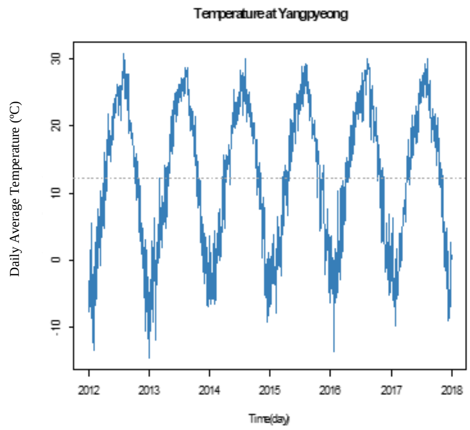

Figure 2. Time series of average daily temperature at the Yangpyeong weather station (2012–2017).

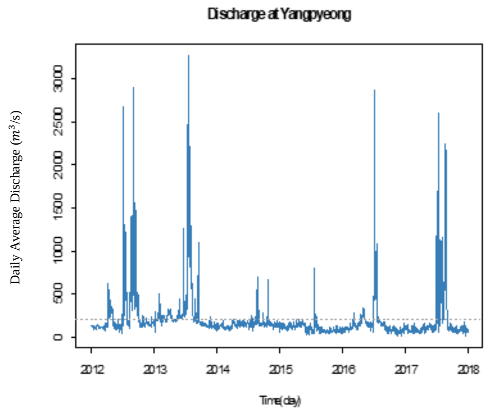

Figure 3. Time series of average daily river discharge at the Yangpyeong-gun (Yangpyeong Bridge) level station (2012–2017).

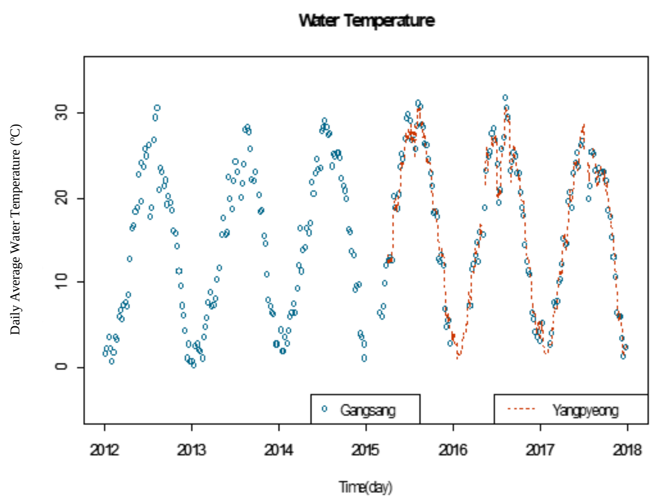

Figure 4. Comparison of water temperatures at the Gangsang and Yangpyeong water quality stations.

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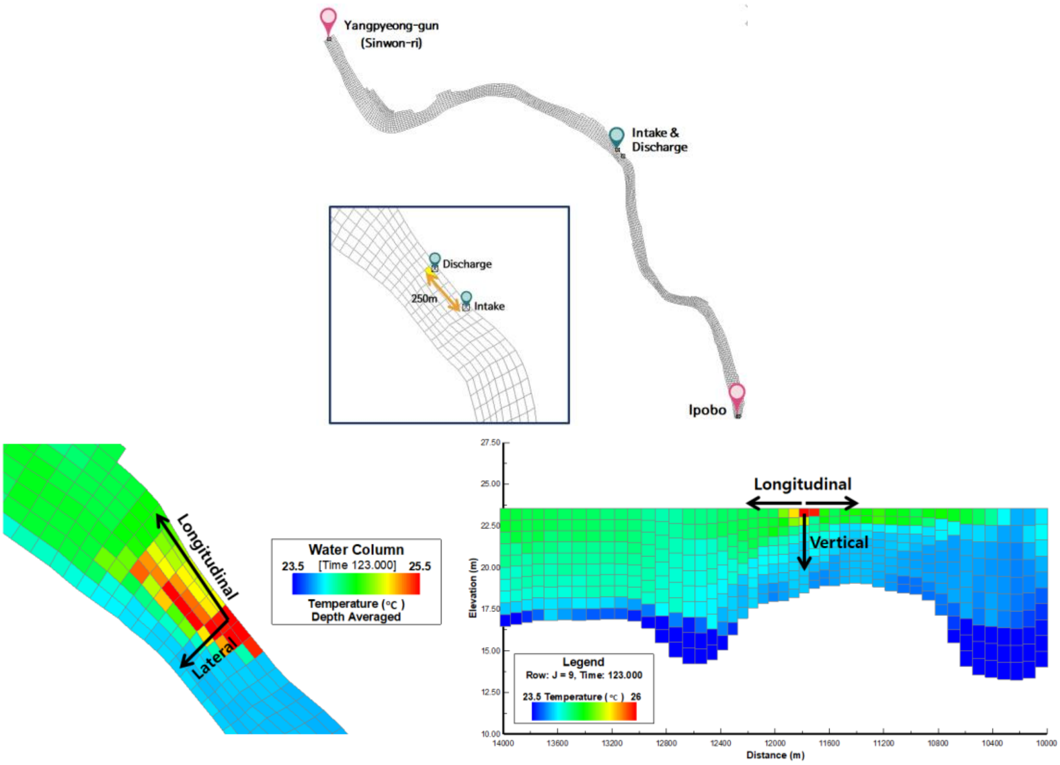

Figure 5. Proposed standard for calculating the water temperature recovery distance in: longitudinal, lateral and vertical direction.

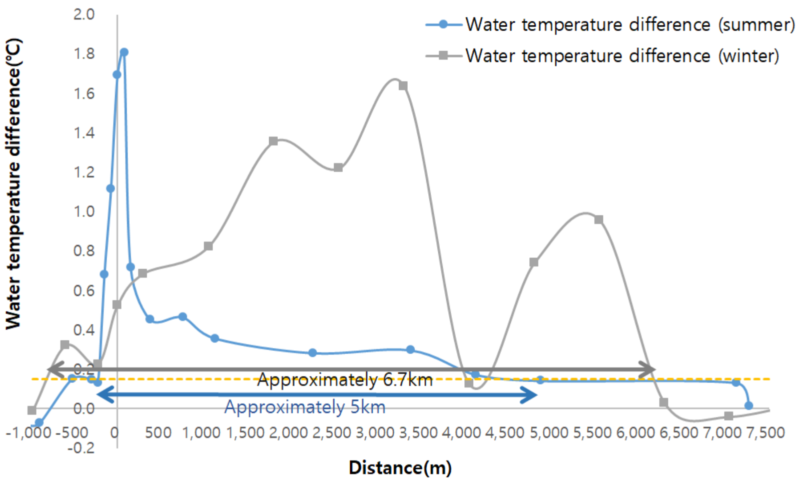

Figure 6. Longitudinal water temperature recovery distance estimation graph

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Figure 7. Distribution of endangered fish species in Korea (Jung et al. [22])

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