A GAME-THEORETIC ANALYSIS OF INTER-KOREAN TRANSBOUNDARY RIVERS

By

KIM, Sung Yun

CAPSTONE PROJECT

Submitted to

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Committee in charge:

Professor Il-Chong NAM, Supervisor ______________________

Professor Nahm Chung JUNG ______________________

Professor Seulki CHOI ______________________

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ABSTRACT

A GAME-THEORETIC ANALYSIS OF INTER-KOREAN TRANSBOUNDARY RIVERS

By

Sung-Yun Kim

The purpose of this paper is to establish a management strategy for the reasonable and equitable utilization of the inter-Korean transboundary rivers through the case of the Imnam Dam on the Bukhan River and the Hwanggang Dam on the Imjin River. As a methodology, game theoretic approach was deployed to explore a solution to the problems of the transboundary rivers between North Korea and South Korea. This paper makes reasonable assumptions about the factors surrounding the transboundary rivers to calculate two Koreas' payoffs respectively, models the process of negotiations between the two Koreas as a sequential move game in which South Korea moves first and North Korea acts next, and analyzes subgame perfect Nash equilibrium according to the flow allocation scenarios. The compensation for North Korea, which is calculated under the assumption as mentioned above, is not sufficient to make North Korea accept the South Korea's proposal. Therefore, this paper suggests not only a new cooperation project in the water resources field to fill the gap of North Korea's payoff, but also takes some measures into account in order to ensure the South Korea's investment recovery during the implementation of the project.

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I. Introduction

Water is a valuable resource for improving the quality of life and developing the national economy. Accordingly, water issues are a matter of concern among regions, countries, and even the entire world. Besides, water is a rare, valuable resource and does not distinguish the territorial borders. Sometimes, those characteristics of water become the reasons conflicts can arise over the use of the transboundary rivers (Barrett 1994).

North Korea, which occupies the upper reaches of the Bukhan River and the Imjin River, unilaterally built the Imnam Dam and the Hwanggang Dam respectively that have diverted the river flow into other watersheds to get more hydroelectricity (Ahn et al. 2011). According to the Long-term Comprehensive Plan (MOLIT 2011), the inflow of the Hwacheon Dam, located at the downstream of the Bukhan River, was estimated to decrease by 1.29 billion m^3 per year after the construction of the Imnam Dam. The plan also reported that the construction of the Hwanggang Dam brought about a decrease of 0.94 billion m^3 per year in the Imjin River basin, deteriorating the downstream water quality and diminishing potential production of fish stocks. South Korea has much difficulty in water supply and river management, such as water shortage in dry seasons and sudden water upsurge in rainy seasons (Korea Environment Institute 2010). This culminated in a disaster in September 2009 with six South Korean casualties and about 143 million KRW property damage, caused by North Korea's sudden discharge of the Hwanggang Dam without any notification in advance (Baek 2016).

The problem of inter-Korean water cooperation requires mutual cooperation, but the two Koreas would not cooperate unless the results of the cooperation between the two Koreas are more beneficial to themselves than those obtained when they do not cooperate. It is because both South Korea and North Korea are individual decision-makers with the power to decide whether to cooperate or not by themselves. Therefore, in order for the two Koreas to cooperate, the strategy of cooperation should be a Nash equilibrium of the non-cooperative game, where South Korea and North Korea are players. The problem is which kind of games the Nash equilibrium is for. To begin with, it should be decided whether this game, where the two Koreas determine whether to cooperate or not in the water resources field, is going to be modeled as a simultaneous move game or sequential move game, in which one of the two Koreas first suggests and the other reacts for the offer. This paper attempts to model and analyze this situation as a sequential move game with the assumption that South Korea will lead water cooperation projects between the two Koreas. In other words, this paper explores the Nash equilibrium by modeling this situation as a sequential move game, where South Korea moves first to suggest to North Korea the flow allocation of the transboundary rivers and inter-Korean water resources cooperation projects, and North Korea moves next to find its best response for South Korea's suggestion. Therefore, not a simple Nash equilibrium, but a subgame perfect Nash equilibrium that is stronger than a Nash equilibrium is going to be deployed.

II. Problem Definition

A transboundary river is a river that runs continuously across national boundaries (Lee 2017). The International Law Association (ILA) defines a transboundary river as a river that includes not only land and underground water but also the geographic range determined by watersheds, extending to more than two countries' territory and sharing a common downstream. This reflects the need to coordinate water resource conflicts among countries through the internationalization of the rivers and effectively regulate environmental pollution by grasping the geographical scope of the transboundary rivers broadly. There are the Bukhan River and the Imjin River in the Han River basin, which are national rivers.

The peaceful use of the transboundary rivers between the two Koreas has following advantages: (1) it promotes the development of inter-Korean relations by preventing military conflict from the perspective of the peace community and prompting exchanges and cooperation through the transboundary rivers; (2) it contributes to the formation of an inter-Korean economic community; (3) it contributes to the formation of an ethnic community by recovering the homogeneity of the people in Korean Peninsula through preserving and co-managing natural ecosystems, excavating and restoring cultural and historical resources in the transboundary river basin (Lee 2011).

The Bukhan River is the first tributary of the Han River, with a watershed area of 10,834.8 km^2, about 41 % of the Han River’s. Among them, the watershed area of North Korea is 3,901 km^2, about 58.5 % of the Bukhan River’s. The Bukhan River originates from Danbalryeong (1,241 m above sea level) near Kumgang Mountain in Gangwon Province, North Korea, flows southward through Faro Lake, Chuncheon Lake and Uiam Lake, and joins the Soyang River. The Imnam Dam in North Korea is located at about 60 km upstream of the Hwacheon Dam, and there is a reservoir dam in the upper stream of the dam with a basin area of 244 km^2. North Korea has diverted the river flow to the East Coast in this dam, and is generating hydroelectric power at the Anbyon Youth Power Plant.

The Imjin River originates from the southern valley of Duryu Mountain in Gangwon Province, North Korea, flows southward into Gyeonggi Province, South Korea, joins the Hantan River, and then meets mainstream of the Han River. The total watershed area of the Imjin River is 8,117.5 km^2, out of which North Korea occupies 62.9 %, 5,108.8 km^2, and South Korea occupies 37.1 %, 3,008.7 km^2. The upstream is mountainous, and most of the mainstream and tributaries form rapid streams. As it flows to the downstream, it becomes gentle and a relatively wide plain is formed in the lowlands of Paju and Munsan area.

There are two fundamental points for an objective discussion on the issue of the transboundary rivers between the two Koreas. The first is that the transboundary river problems, in which the upstream and downstream areas are clearly separated by borders, are fundamentally unsettled by measures taken by only one of the two Koreas, especially the downstream ones. The second is that there is no official international law or mechanism to co-ordinate or resolve disputes between the two Koreas on the transboundary rivers. When social interests were focused on this issue in the past, some people argued that South Korea should sue North Korea to the international organizations. However, since both South Korea and North Korea have not signed international UN conventions, the United Nations is unlikely to intervene on this issue unless both of the two Koreas bring suit cases against each other to the UN for the transboundary river problems.

In 1997, the United Nations Convention on the Law of the Non-Navigational uses of International Watercourses presented the basic principles and directions for the joint management of the transboundary rivers that have been discussed internationally. However, this agreement is not a compulsory regulation that each country has to obey mandatorily. A State becomes a compulsory country only after signing and ratifying this Convention, and the two Koreas are not included in the list of the compulsory countries. In the end, the issues of the transboundary rivers between the two Koreas cannot help but to be solved through negotiation and cooperation between the parties. Considering only the transboundary river problem, South Korea located in the downstream is always in a disadvantageous position due to unidirectionality, and becomes more and more disadvantageous over time.

Historically, one of the things accepted important in the use of inter-country or inter-regional transboundary rivers is customary water use or prescriptive water rights. In other words, the behavior of river use that has been accepted for a long time is respected.

The Bukhan River and the Imjin River have inter-Korean conflict factors. The transboundary rivers in the upstream located in North Korea have high runoff coefficient because the rivers flow along rugged mountain canyons. Therefore, the flow rate increases rapidly in the case of heavy rain, which can result in flood damage in the middle and downstream areas.

For example, North Korean forests located in the upstream of the Bukhan River are devastated, which may make flood damage propagate to the Seoul metropolitan area when the discharge of the Imnam Dam is implemented during heavy rain. In addition, after the construction of the Imnam Dam in North Korea, the annual inflow amount of the Bukhan River decreased by 1.29 billion m^3/yr, and the South Korea is suffering from a decrease in hydroelectric power generation water and river maintenance water, a change in the environment, and deterioration in water quality. Especially, Sunwoo (1986) estimated that the 370 MW/day of the total power generated by the five consecutive hydroelectric power plants, located at the downstream of the Bukhan River, would diminish by 104 MW/day (28.2%) if the upstream inflow is blocked after the construction of the dam.

On the other hand, the Imjin River had severe flood damages in the middle and downstream areas because of heavy rain in the past, and the downstream of the Imjin River is in danger of flooding the surrounding area as the level of the riverbed rises because the sediments from the middle and upper stream accumulate. Moreover, North Korea constructed the Hwanggang Dam and diverted the river flow of the Imjin River to the Yesung River to get more hydroelectric power, resulting in a 0.94 billion m^3/yr decrease in annual inflow. During the dry seasons, the decrease in the flow rate of the river becomes severe, which causes side effects such as seawater infiltration and ecosystem disturbance in the downstream, and it may threaten the agricultural water supply for Yeoncheon and Paju region. Particularly, due to the discharge of the Hwanggang Dam in the case of heavy rain, flood damage is more likely to occur in such downstream area as Yeoncheon, Paju, etc. This culminated in a disaster in September 2009 with six South Korean casualties and about 143 million KRW property damage, caused by North Korea’s sudden discharge of the Hwanggang Dam without any notification in advance (Baek 2016). To prevent this situation from happening, South Korea constructed Gunnam Flood Control Dam in the Imjin River and Hantangang Flood Control Dam in the Hantan River, the tributary of the Imjin River (Lee et al. 2008).

As mentioned above, there have been several cases of conflicts between the two Koreas due to the different viewpoint in the transboundary river use and management. South Korea located in the downstream of the transboundary rivers has been unable to slow down the concerns and tensions about the transboundary rivers. In 2000, the South Korean government tried to cooperate with the North Korean government in the Imjin River Flood Prevention Project to mitigate the transboundary river conflicts between them. At the second inter-Korean ministerial talks (August 2000, Pyongyang), the North agreed to the Imjin River Flood Prevention Project, which made the cooperation atmosphere boom. Since then, in the Imjin River Flood Prevention Working Group and the Inter-Korean Economic Cooperation Committee, agreements for the Imjin River Flood Prevention, inter-Korean joint investigation, provision of equipment and provision of measurement data have been discussed many times, but there has been no real achievement. In the 13th Inter-Korean Economic Cooperation Promotion Committee (April 2007, Pyongyang), an attempt was made to adopt a consent form for the supply of equipment and the cooperation of local visits and technical support, but it did not succeed neither. In September 2009, the Imjin River accident that caused six South Korean casualties occurred, and in October of the same year, the Imjin River Flood Prevention Practical Meeting was held. At this time, the North expressed its condolences due to the accident in Imjin River and agreed to give advance notice to prevent accidents from recurring in the future. Through the talks, North Korea agreed to discuss the next round of talks on the prevention of floods and the shared use of inter-Korean transboundary rivers, but it did not lead to concrete consultations. Until now, the Imjin River Flood Prevention Project is the only cooperation project, but as mentioned above, the Imjin River Flood Prevention Project has only been agreed upon, and concrete discussions and implementations for establishing practical measures have not been made yet.

III. Literature Review

South Korea, which is geographically located in the downstream of the transboundary rivers, is suffering from the various problems caused by North Korea's unilateral use of water resources in the upstream region (Korea Environment Institute 2010). In the case of conflicts involving the transboundary rivers, there are no universally accepted principles (Korea Institute for National Unification 2006). Therefore, constant consultation between the two Koreas is required to solve these issues. Nevertheless, the inter-Korean cooperation on the transboundary rivers has been much influenced by the political and military situations, although the cooperation on the water resources has the high feasibility in ecological, economic, and technological fields excluding the ideology and politics (Korea Institute for National Unification 2006). As can be seen from the cases of the Kaesong Industrial Complex and the Mt. Kumgang Project, North Korea has shown an active attitude toward the cooperation that is practically beneficial to itself (Lee et al. 2008). Therefore, this paper makes an effort to estimate the monetary value of the additional water that North Korea were to furnish, explore the new projects that South Korea would provide North Korea with as a compensation.

A. The Cooperation Projects concerned with the Korean Transboundary Rivers

The Korea Institute for National Unification (2006) suggested that it is necessary to distinguish between short, mid and long-term projects according to the feasibility and urgency of inter-Korean exchanges and cooperation on the transboundary rivers.

For the short term projects, it would be desirable to commence the cooperation that the two Koreas have already agreed upon, but have not yet implemented, for example the basic co-research on the transboundary rivers, the formation of a meteorological observation network, the establishment of a transboundary river cooperation committee, and a joint disaster prevention (Korea Institute for National Unification 2006).

As for the mid and long term projects, the following can be found in the literature. According to the Hyundai Research Institute (2006), the aggregate reserves of the Imjin River estuary are estimated to be 1.08 billion m^3. The dredging work to collect the sand in the region not only makes it possible to meet the annual total demand of the Seoul metropolitan area of 45 million m^3 for 25 years, but also helps prevent the flood damage in the downstream area of the Imjin River, which is occurring repeatedly in every summer, because the water level of the Han River estuary is reduced by about 1 m. The Korea Institute for National Unification (2006) suggested reforestation, the cooperation on water resources and ecosystem management and conservation. In order to solve the electric power shortage of North Korea caused by water supply to South Korea, Lee et al. (2008) suggested several models, such as the installation support of pumping-up power plant facilities in North Korea and the renovation of existing outdated hydroelectric dam facilities.

B. Game Theory in Water Conflicts

A variety of approaches based on the economic theory have been made to the transboundary river problem, and one of the typical methods is game theory. John von Neumann and Oskar Morgenstern first introduced formally the game theory in their book published in 1944, *Theory of Games and Economic Behavior* (Teasley 2009). Game theory analyzes the conflict and cooperation among players mathematically

(Madani 2010). It explores strategies for players who participate in the game to predict their costs and profits from the decisions made by the other players and to determine the best response they can take based on their predictions (Teasley 2009). The game theoretical approach to the transboundary rivers has been set up and analyzed as a non-cooperative game in order to study the counter-strategies for confrontation and conflict. There have been many cases which adopted non-cooperative game theory to include unidirectional externalities in the modeling (Barrett 1994). Madani (2010) examined whether game theory can be applied to water management and dispute resolution by using a series of non-cooperative water resources games, and explained that considering evolution path of the game is important during the research on the dynamic structure of water resources. Eleftheriadou et al. (2008) quantified the consequences of flow reduction, according to the various scenarios by using the concept of game theory in a case study of Greek-Bulgarian negotiations on Nestos/Mesta transboundary rivers, and provided a background for preparing the compromise measures acceptable to both countries. The authors also argued that linking other issues irrelevant to water resources games could broaden the available options of the nation and avoid the unreasonable consequences of "power" unbalance. According to the study conducted by Just and Netanyahu in 1998 (as cited in Eleftheriadou and Mylopoulos 2008), negotiation sometimes leads to the dominance of a strong player due to the severe asymmetry between the parties, and the concept of equity is easily ignored. In such a case, it may be beneficial for weak players to integrate the other issues. As for inter-Korean transboundary rivers, Choi and Lee (2008) applied the cooperative game theory approach to the Bukhan River to quantify the conditions of cooperation and reward for the best mutual benefit of the two Koreas.

No research has been found that employs an analytical method, which this paper will use, to model conflicts and cooperations on the transboudary rivers as a sequential move game and seek subgame perfect Nash equilibrium.

IV. Model and Equilibrium

A. Modeling the Games

This papers models the situation surrounding the cooperation between South Korea and North Korea about the water resources belonging to the Bukhan River and the Imjin River as a sequential move game of complete information with the following characteristics.

Players: Players in this non-cooperative game over the transboundary rivers are South Korea and North Korea. A game player must have a means that can influence the other player's decision, and make negotiation and coordination possible. In the case of the inter-Korean transboundary rivers, which are clearly separated as upstream and downstream, the upstream nation (North Korea) has a means to adjust the flow rate, but the downstream nation (South Korea) has no clear means to control the activity of the upstream (Choi and Lee 2008).

Structure of the game: South Korea moves first and makes an offer to North Korea. North Korea observes the move by South Korea and decides whether to accept or reject the offer of South Korea.

Actions North Korea can take: South Korea offers to North Korea flow allocation rate for the transboundary rivers and an acceptable amount of compensation for the water exceeding South Korea's prescriptive water rights (this paper estimates it as 50 %). Besides, inter-Korean cooperation projects in water resources field and South

Korea’s investment recovery plan are included as part of South Korea's proposal in order to meet the compensation amount for North Korea.

Actions North Korea can take: North Korea can accept or reject South Korea's proposal.

Payoff to South Korea: The profits of hydroelectric power generation, obtained from the five consecutive dams in the Bukhan River as the inflow from the upstream increases, and the potential water usage profits, gained from the Bukhan and Imjin River basin, are to be calculated. Flood prevention and environmental improvement profits will not be taken into account because they are difficult to quantify in reality. In particular, South Korea pays half of the profits it gains from the water exceeding its prescriptive water rights as a compensation for North Korea.

Payoff to North Korea: The profits of hydroelectric power generation and the potential water usage profits in the river basins are calculated. As in South Korea, flood prevention and environmental improvement profits are not considered. North Korea receives half of the profits South Korea gains from the flow rate exceeding its prescriptive water rights.

In this game model, South Korea is assumed to be the first mover. It is because South Korea is more economically affluent than North Korea, and it has much economic development experience. Therefore, it is more feasible for South Korea to establish a plan for economic cooperation and to suggest it to North Korea. Another reason is that the author approaches the issue from the standpoint of the Korea Water Resources Corporation, which is operated by the South Korean government, and is planning cooperation projects on the transboundary rivers.

B. The Fundamental Data and their Sources

The figures and their sources of the basic data used to calculate the payoffs of the two Koreas are as follows.

Flow Reduction after the Construction of Imnam Dam and Hwanggang Dam

The Long-term Comprehensive Plan (MOLIT 2011) estimated that the inflow of the Hwacheon Dam, located at the downstream of the Bukhan River basin, has decreased by 1.29 billion m^3 per year because of the construction of the Imnam Dam. The plan also reported that the construction of the Hwanggang Dam caused a flow reduction of 0.94 billion m^3 per year in the Imjin River basin.

The Unit Price of Dam Water and the Water Use Rate

As of 2018, the unit price of dam water is 52.7 KRW/m^3, which was approved by the Minister of Land, Infrastructure and Transport (MOLIT) in accordance with Article 35 of the Act on the Construction of Dams and Surrounding Areas, etc., and the same rate is applied nationwide for balanced development of the local communities (K-water 2018). In general, not all the water flowing in the river is used. Long-term Comprehensive Plan for Water Resources (MOLIT 2016) provides that the water use ratio to the total available runoff in South Korea is about 48.95 %. On the other hand, the water use ratio of North Korea is assumed to be 20 % considering that the water use ratio of South Korea was 23 % in the 1980’s (Choi and Lee 2008).

The Unit Price of Electricity

In South Korea, alternative firepower assessment techniques are being used to evaluate the hydroelectric power generation benefits. However, since the privatization of power generation subsidiaries, Korea Electric Power Corporation (KEPCO) seems to have adopted the unit price, which is used to purchase the nuclear power, as the unit price for evaluation. The unit price of nuclear power is 63.80 KRW/kWh, which is the average of the latest three year price data based on the Statistics of Electric Power in Korea. For reference, Table 1 shows KEPCO's average purchase price (KRW/kWh) for the last three years of nuclear, LNG, combined cycle, hydro, etc. (KEPCO 2015~2017).

Table 1. Average Purchase Price by Energy Source

Nuclear	Bituminous	Domestic Coal	Oil	LNG	Combined Cycle	Hydro	Pumping
63.80	76.34	97.41	141.86	134.49	112.81	100.78	115.71

Decrease in Annual Gross Hydroelectric power Generation of South Korea

The decrease in the annual gross hydroelectric power generation of South Korea is considered only in the Bukhan River basin because there is no hydroelectric power plant in the South Korean Imjin River basin. Sunwoo (1986) estimated that the 370 MW per day of the total power generated by the five consecutive hydroelectric power plants, located at the downstream of the Bukhan River, would diminish by 104 MW per day (28.2 %) if the upstream inflow is blocked after the construction of the dam.

Annual Generation of Transboundary River Hydropower Plants in North Korea

It is difficult to acquire accurate data on the operational status of the North Korean hydroelectric power plants located on the transboundary rivers. Thus, the only way to estimate the annual hydroelectric power generation is by using the facility capacities and utilization rates of the hydroelectric power plants. According to the North Korea Information Portal (MoU 2017), the total installed capacity of the Anbyeon Youth Hydropower Plant is 324 MW/day: those of the No. 1 and No. 2 power plant are 300 MW/day and 24 MW/day respectively. Meanwhile, the Hwanggang Dam diverts its river flow to the Yesung River basin and there are six Yesung Youth Hydropower

Plants from No.1 to No.6 with the total 90 MW/day capacity (United Nations Framework Convention on Climate Change 2016 as cited in Hyundai Research Institute 2016).

Major Statistics Indicators of North Korea 2016 (Statistics Korea 2016) says that North Korea's hydroelectric power plant utilization rate was about 37 % in 2013 and Kim (2018) argued that the hydroelectric power plant utilization rate in North Korea dropped from 41.5 % in 1990 to 31.1 % in 2016. The average utilization rate of North Korean hydroelectric power plants has become lower because North Korea cannot afford to rehabilitate the seriously deteriorating facilities. Fifty three percent of North Korea's hydroelectric power plants were constructed during the Japanese occupation, and the facilities used for more than 20 years account for 84 % of the total capacity (Choi and Lee 2008). Therefore, the utilization rate of the Anbyeon Youth Hydroelectric Power Plant and the Yesung Youth Hydroelectric Power Plant can be estimated to be somewhat higher than the North Korea’s average because the plants have been constructed relatively recently. Nonetheless, North Korea has also suffered from frequent breakdowns and performance deterioration of its newly built hydroelectric power plants owing to the lack of technological assistance from abroad (Kim 2018). Taking all these circumstances into account, it is assumed that the hydroelectric power plants generate electricity about 70 % of their facility capacity. As a result, the total annual hydroelectric power generation of the hydroelectric power plants can be calculated as about 2,538.65 GWh/year.

C. Net Profit from Transboundary Rivers under Water Allocation Scenarios

The payoffs of South Korea and North Korea are to be calculated according to the following scenarios for flow allocation of the transboundary rivers (South Korea : North Korea): (1) 0 : 10 (After construction of North Korean dams); (2) 5 : 5 (South

Korea’s prescriptive water rights); (3) 7 : 3; (4) 10 : 0 (Before construction of North Korean dams).

Before Construction of the Imnam Dam and the Hwanggang Dam

The border areas in North Korea, located in the upstream of the Bukhan River and the Imjin River, were not developed until the construction of the Imnam Dam and the Hwanggang Dam. Therefore, the practical economic benefit of North Korea from those areas was insignificant. The nearby areas of the transboundary rivers had used little amount of water for drinking and agriculture, which caused no significant change in the inflow of the downstream.

South Korea utilized the water flowing along the Bukhan River for living, industrial and agricultural purposes of the Seoul metropolitan area, but its significance in terms of water use was not so high. On the other hand, the water of the Imjin River was considered precious for living, industry, and agriculture. In South Korean territory of the downstream of the Bukhan River, there are five consecutive dams, including Hwacheon, Chuncheon, Uiam, Cheongpyeong and Paldang Dam. All of the dams are equipped with the hydroelectric power plants so that the plants generate a total of 370 MW per day. If the inflow is cut off due to the construction of the Imnam Dam in the upstream of the Bukhan River, the total hydroelectric power generation will decrease by 104 MW per day, or 28.2 %, out of 370 MW (Sunwoo 1986). Meanwhile, no hydroelectric power plant is installed in the South Korean region of the Imjin River downstream. Therefore, the construction of the Hwanggang Dam does not affect the South Korean benefits from hydroelectric power generation.

Assuming that the unit price were 63.80 KRW/kWh and 104 MW/day were generated, it could be seen that South Korea benefited a maximum of 581.24 hundred million KRW per year from the hydroelectric power generation by using the upstream inflow of the Bukhan River. Choi and Lee (2008) assumed that the net profit does not exceed 10% of the total sales calculated based on the unit price of electric power. It is because in South Korea the investment compensation corresponding to the net profit did not exceed 6~7% of the unit price according to the past records.

Assuming that the annual inflows of the Bukhan River and the Imjin River drop by 1.29 billion m3 and 0.94 billion m3 respectively (MOLIT 2011), South Korea will be hindered by its use of living, industrial and agricultural water. Of course, in the case of the Bukhan River, there is no water shortage in the Seoul metropolitan area at present with the entire water demand met without any severe difficulty, but the potential water source will be lost under a water shortage situation. On the other hand, the Imjin River is already experiencing serious difficulties in the management of living and agricultural water in the dry seasons (Baek 2009). As of the end of 2018, the price of the dam water is 52.70 KRW/m3 (K-water 2018). The loss due to the water blockage can be calculated as 1,175.21 hundred million KRW per year based on the price of the dam water, but it should be adjusted since generally not all the water which flows along the river is used. It will be about 575.27 hundred million KRW per year if 48.95 % is applied to the calculation, which is presented as the river water utilization rate of South Korea by MOLIT (2016).

In conclusion, South Korea has benefited about 581.24 hundred million KRW per year by hydroelectric power generation and has secured some 575.27 hundred million KRW in potential benefits per year for water use. If 10% (58.12 hundred million KRW) of benefits from hydroelectric power generation and 100% (575.27 hundred million KRW) of benefits from water use are regarded as a net profit, the total benefits of South Korea can be calculated as the following equation; 58.12 hundred million KRW + 575.27 hundred million KRW = 633.39 hundred million KRW.

Table 2. Net Profit from Transboundary Rivers before Dam Construction (hundred million ₩/yr)

Index	Power Generation	Water Use	Total
North Korea	-	-	-
South Korea	58.12	575.27	633.39

After Construction of the Imnam Dam and the Hwanggang Dam

North Korea can get profit from the hydroelectric power generation and the potential water use by constructing the Imnam Dam and the Hwanggang Dam. In the previous Section, the hydroelectric power generation was estimated to be 2,538.65 GWh/year by multiplying the facility capacities and the facility utilization rates since it is impossible to obtain accurate data on the electricity generation from the North Korean hydroelectric power plants located in the transboundary river basins. If the net profit of North Korea is calculated according to the exact same way to calculate South Korea's, it will be 161.97 hundred million KRW per year.

Considering that the water use rate to river runoff in South Korea was 23% in 1980, the water use rate of North Korea is assumed to be 20% of the total inflow blockage (Choi and Lee 2008). If 20% water use rate is applied, it can be confirmed that potential water use benefit is about 235.04 hundred million KRW. Consequently, North Korea can earn a net profit totaling 397.11 hundred million KRW annually, including the potential benefits of water use.

Table 3. Net Profit from Transboundary Rivers after Dam Construction (hundred million ₩/yr)

Index	Power Generation	Water Use	Total
North Korea	161.97	235.04	397.01
South Korea	-	-	-

Table 4 shows the net profits of North Korea and South Korea, according to various flow distribution scenarios including the above mentioned scenarios.

Table 4. Net Profit from Transboundary Rivers under Water Allocation Scenarios (hundred million ₩/yr)

Index	Allocation	Power generation	Water use	Payoff
North	10	162	235	397
South	0	-	-	-
North	5	81	118	199
South	5	29	288	317
North	4	65	94	159
South	6	35	345	380
North	3	49	70	119
South	7	41	403	443
North	2	32	47	79
South	8	46	460	506
North	1	16	24	40
South	9	52	518	570
North	0	-	-	-
South	10	58	575	633

The value of water in South Korea is higher than in North Korea. In the present situation, in which North Korea has completely shut off the flow of water to South Korea through the transboundary rivers, since North Korea has a relatively larger capacity of hydroelectric power facilities than South Korea, the benefits of hydroelectric power generation are greater than that of South Korea. However, since the river water use rate in North Korea is significantly lower than that in South Korea, the benefits derived from water use are much less than those in South Korea. As a result, the greater the share of South Korea in the transboundary river flow, the greater the total profits of game players. However, in this case, North Korea cannot use the river flow for any purpose, including living, industrial and agricultural water use. This will not be acceptable to North Korea because it incurs not only the dissatisfaction of the North Korean people, but also the sunk cost resulting from the inability to utilize the dams and hydroelectric power facilities already built. Considering these situations of North

Korea, flow allocation of South Korea and North Korea, (7 : 3) is selected.

Figure 1 shows an extensive form of a game, where South Korea first offers to North Korea the three flow allocation options: (5 : 5), (7 : 3), and (10 : 0) and North Korea can accept or reject it.

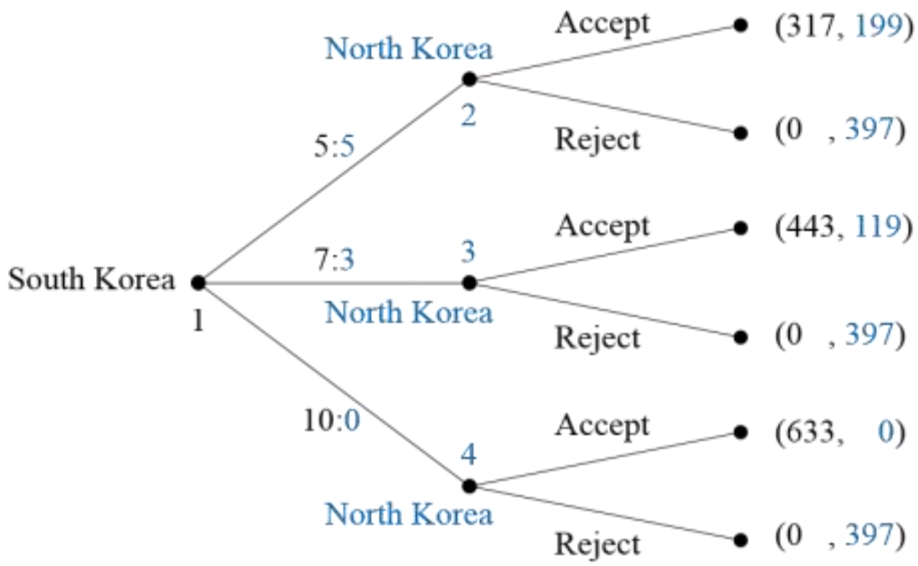

Figure 1. Modeling the Game without Compensation

To obtain the subgame perfect Nash equilibrium for the sequential move game with complete information, first move to the lowest level of the game and then select the optimal move from the perspective of the player who is making a decision at that node. After that, the optimal move is marked with an arrow and a bold line. When this process is completed at that level, move to the next upper level and repeat the process of selecting the optimal move at each node in the same manner.

At decision node 2, North Korea chooses “Reject” because its payoff (397) when it selects “Reject” is larger than its payoff (199) when it selects “Accept”. North Korea chooses “Reject” at Decision nodes 3 and 4 for the same reason (see Figure 2).

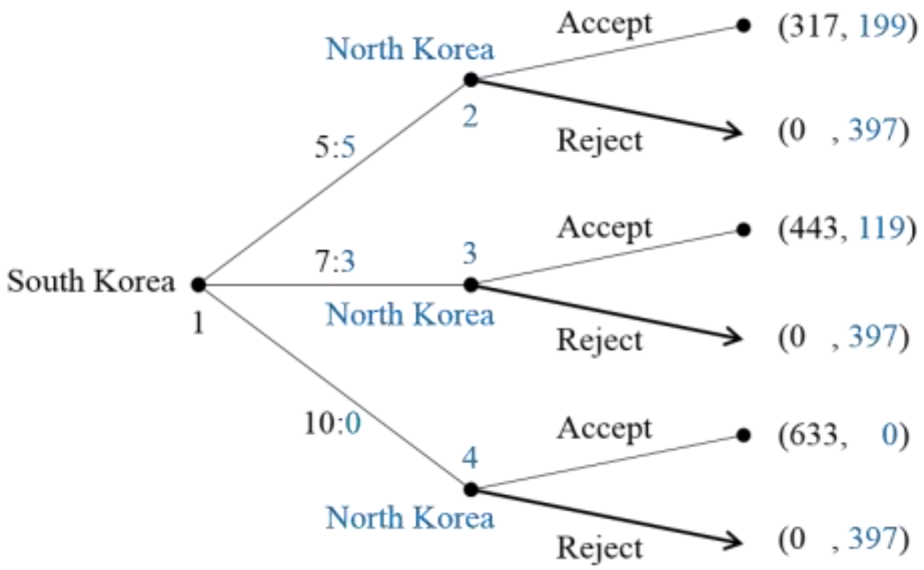

Figure 2. Modeling the Game without Compensation (Rollback)

Now that the optimal actions for all the decision nodes at that level were selected, the next step is to go to the upper level, decision node 1, and then when South Korea chooses the optimal move among (5 : 5), (7 : 3), and (10 : 0), South Korea's payoff becomes 0 regardless of which one is selected. In the end, South Korea becomes indifferent about all the strategies South Korea can take (See Figure 3).

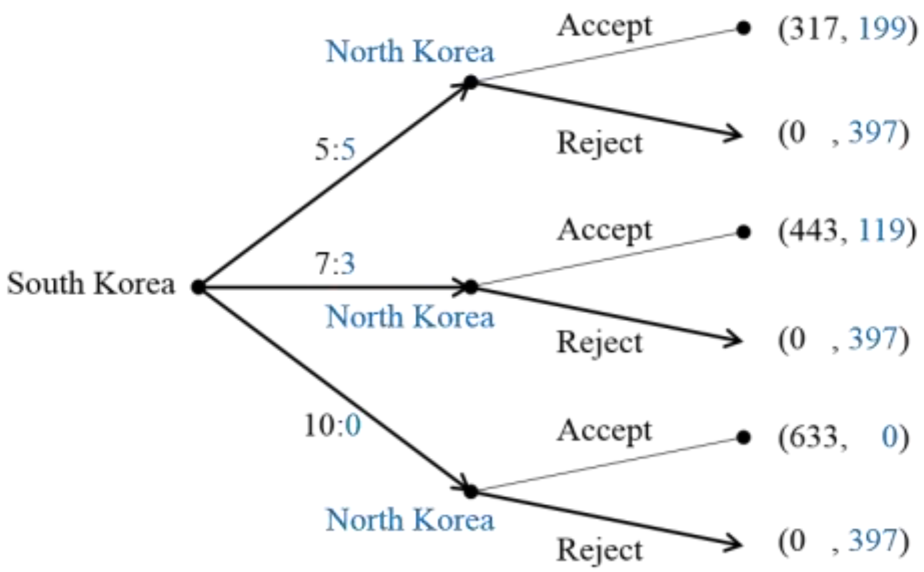

Figure 3. Modeling the Game without Compensation (SPNE)

As can be seen in Figure 3, the subgame perfect Nash equilibrium is that South Korea offers flow allocation scenarios: (5 : 5), (7 : 3), (10 : 0); North Korea chooses “Reject” for all those scenarios. In a sequential move game without compensation, there is no reason for North Korea to accept the South Korea's proposals because the payoff of North Korea in the status quo is greater than payoff that South Korea can offer in any case.

Next, Figure 4 shows an extensive form of a game, where the two Koreas evenly divide South Korea’s profit gained from the additional water as a compensation.

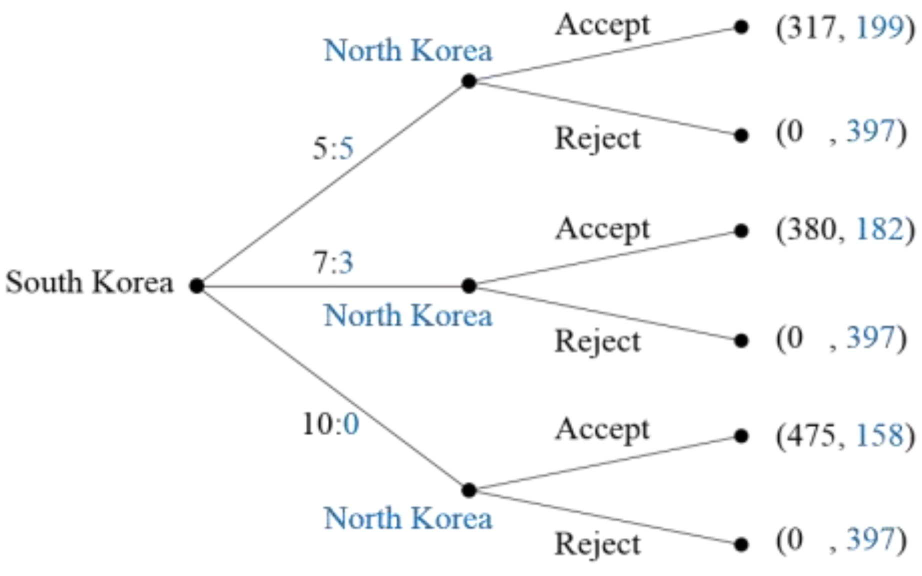

Figure 4. Modeling the Game with Compensation

The subgame perfect Nash equilibrium, obtained through the same rollback process used in the previous game, is that South Korea offers flow allocation scenarios: (5 : 5), (7: 3), and (10 : 0); North Korea selects “Reject” in any case. Although North Korea's payoff has increased as South Korea has rewarded North Korea, in no case North Korea can have payoff greater than 397 which North Korea can obtain when it chooses “Reject” (see Figure 5).

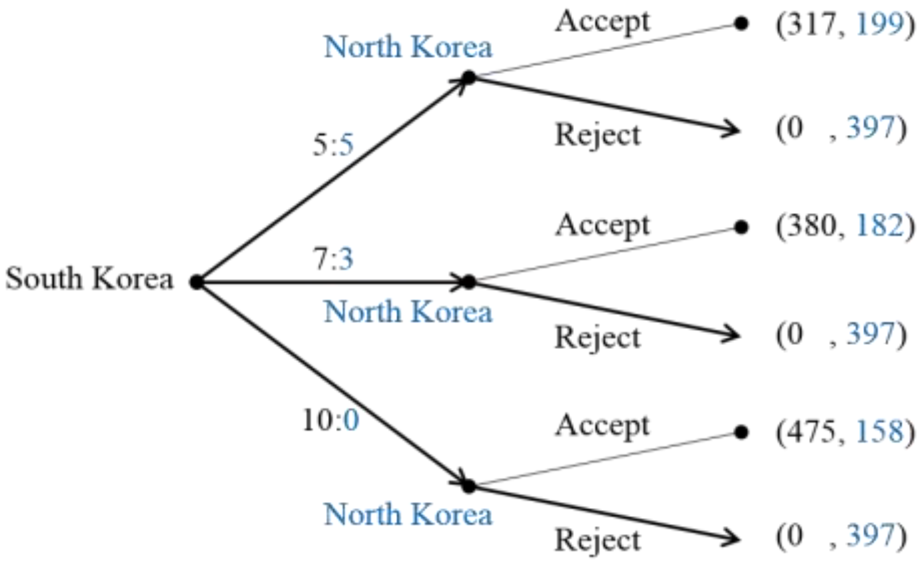

Figure 5. Modeling the Game with Compensation (SPNE)

Finally, the game in case 3, where South Korea does not merely compensate for the excess amount over 50% of water quantity, but rather utilize the compensation amount to implement cooperative projects related to water resources in the North Korean territory, giving each country the extra profit, α, is presented in the Figure 6 as an extensive form.

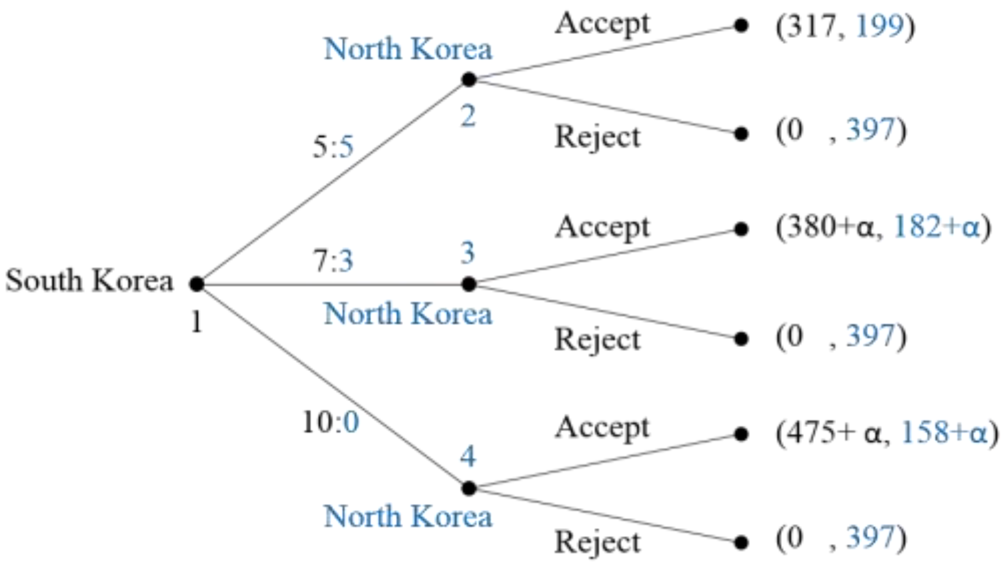

Figure 6. Modeling the Game with Inter-connected Compensation from Cooperation Projects

In order for South Korea to make North Korea, which are standing at node 3, select "Accept" as the optimal move, the payoff, (182+α) when North Korea chooses "Accept" should be equal to or greater than the payoff, (397) when North Korea chooses "Reject". Therefore, North Korea would choose "Accept" at node 3 when the North Korea's profit, α from the water resource cooperation projects is more than 21.5 billion KRW per year, and then South Korea selects (7 : 3) at node 1. The subgame perfect Nash equilibrium here is that South Korea suggests (7 : 3) flow allocation with cooperation projects; North Korea chooses “Accept” at node 3, and chooses “Reject” on nodes 2 and 3 (see Figure 7).

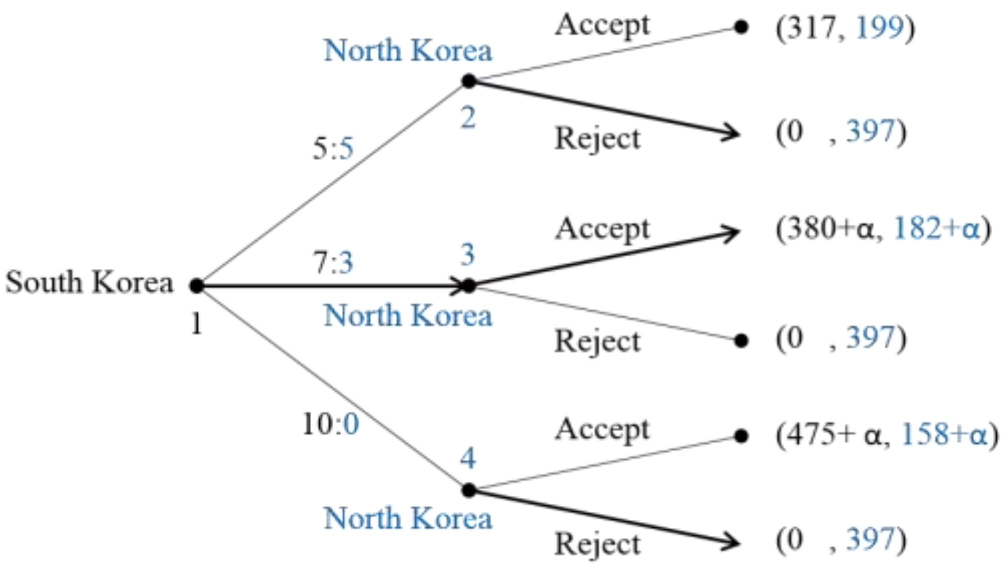

Figure 7. Modeling the Game with Inter-connected Compensation from Cooperation Projects (SPNE)

V. Interpretation and Policy Recommendation

The problem between the two Koreas surrounding the transboundary rivers is caused by the fact that North Korea unilaterally changed the river flow to generate more electricity from the upstream, which has a great impact on South Korea's use of water. It is contrary to the international practice of the transboundary rivers that should restrict such activities. The most ideal way for South Korea is that North Korea abolishes the watershed-modified hydroelectric power generation on the transboudary rivers and guarantees the same inflow to South Korea as it was before construction of the dams.

As can be seen in Table 4, when South Korea uses all of the transboundary rivers flow rate, it maximizes South Korea's payoff as well as the sum of each game player's payoff. However, in that case, North Korea cannot cope with the future water demand, and the inability to use the dam and the hydroelectric facilities that already been built will burden North Korea additional sunk cost. Therefore, it becomes a dominated strategy for North Korea. A common solution in this situation is that South Korea makes an appropriate compensation to the North Korea, and North Korea allow a certain amount of water flow into South Korea through the transboundary rivers.

What is important here is the level, method and timing of compensation. First, the level of compensation depends on the flow allocation rate to South Korea. Choi and Lee (2008) assumed that South Korea would have a prescriptive water rights of up to 50 % of the total flow rate that had flowed to South Korea prior to the construction of the dams. Therefore, it is not appropriate for South Korea to compensate North Korea for inflow less than 50 % because it violates the principle of equitable use of the transboundary rivers. To put it another way, if North Korea discharges more than 50 % of the total flow rate to South Korea, South Korea must compensate only for the amount exceeding 50 %. In addition, this transaction can only be concluded if the amount of compensation to North Korea is greater than the profits North Korea can obtain by itself without complying with South Korea's proposal.

In Chapter 4, the sequential move games, in which South Korea becomes the first mover, were modeled; (1) when South Korea did not compensate for the additional water; (2) when South Korea simply compensates for flow rates exceeding 50 %; (3) when the two Koreas utilize the compensation amount for the additional water to implement cooperation projects and share profits. Then, the subgame perfect Nash equilibrium was obtained in each case. As a result, it was confirmed that in case 1 and 2, North Korea would reject any proposal from South Korea. South Korea can expect that North Korea will accept South Korea’s 7 : 3 water allocation proposal only when North Korea gains more than 21.5 billion KRW every year in case 3.

It is important that the compensation method should provide an appropriate justification and a substantial benefit to both parties. The North Korean hydroelectric power facility modernization project, which means improving performance such as output and efficiency by replacing all hydroelectric power generation facilities except civil structure, can be suggested. North Korea has adopted self-reliance principles to develop its own economy without any aid from abroad. Therefore, the dependence on hydroelectric power in the energy sector is as high as 60 % of the total power supply. Nevertheless, North Korea is experiencing a great deal of difficulty in maintaining the hydroelectric power facilities, which makes facility utilization rates be falling continuously.

The large-scale hydroelectric power plants in North Korea were built during the Japanese colonial period or around the Korean War with Russia’s support. At present, North Korea is facing serious problems on maintaining the hydroelectric power facilities as technical support and supply of parts are stopped from China, Russia, etc. The lack of parts is so serious that the North Korean engineers disassemble a normally operating hydroelectric power generator to take the needed parts from it and repair the other failed generator. This problem is also linked to the poor performance of the newly constructed hydroelectric power plants. In the hydroelectric power plants built by North Korea with its own technology, the lack of technology not only makes the hydroelectric power generation of the plants less than half of the designed output, but also causes various technical problems (Lee et al. 2012).

In promoting this project, South Korea must actively design investment reimbursement and profit sharing schemes. It is because the direct investment cost recovery linked to the profit structure of businesses is often difficult, given the socialist economy approach. Therefore, the reimbursement plan not related to the hydroelectric power facility modernization project should be established in economic and non-economic way. Here, the economic way means securing the operating rights of the infrastructure and being exempted the South Korea-Russia Energy Infrastructure Travel Fares, and non-economic way means collection in the form of a political, cultural or social reward such as North Korea's nuclear dismantlement, regular visits of separated families, etc. (Kim et al. 2012).

In the process of this project, it would be a good strategy to secure the sustainability of the project by deliberately motivating North Korea's allies to participate in the project, evolving the project into a multilateral cooperation system.

The timing of a transaction is the most important thing. In the international relationships, trading with such a compensation can be facilitated if the economic gap between the riparian countries is greater, and the water allocation impact on their economy between the upstream and downstream is smaller. The greater the gap in economic power, the greater the difference in relative value for water use, which makes it easier for the countries with the superior economic power to compensate their counterparts for the amount to which they are acceptable. It cannot be overstated that the sooner, the better to make a reasonable compromise at the present stage in which the difference in the economic strength of the two Koreas is large and the stress caused by water demand is not high in North Korea. If the situation where North Korea is allowed to unilaterally exploit the water of the transboundary rivers persists, South Korea will continue to be in a more and more unfavorable position (Choi and Lee 2008).

VI. Conclusion

The most desirable solution for the transboundary river management is for the riparian countries to conclude agreements on the equitable and rational use of the rivers in accordance with the principles of the international law, and to create watershed communities. As a result, the riparian countries can use and manage the water efficiently under the condition that they do not harm the health of the river environment. However, if the reliance on the transboundary rivers is high, the management criteria are determined mainly by the riparian countries' concern, power, and closeness among themselves rather than the international customs or principles. Therefore, it is more realistic and reasonable to attempt to solve the transboundary river problems by analyzing them through game theory rather than approaching them in accordance with the international law or the water right principles. The same is true for the problems of the inter-Korean transboundary rivers. It would be only a diplomatic rhetoric to emphasize the principles of the international laws under the present condition that there is no agreement, treaty, or consent to control the North Korea's unilateral exploitation of the transboundary rivers. Therefore, the game-theoretic approach based on economic interests is the most persuasive approach to the inter-Korean transboundary river problems, considering the present situation that full-scale inter-Korean exchanges have yet to occur. For this reason, this paper has tried to solve the transboundary river problems between the two Koreas through the approach of non-cooperative game theory. More specifically, this paper makes reasonable assumptions about the factors involved in inter-Korean water cooperation surrounding the transboundary rivers; models the process of negotiations between the two Koreas as a sequential move game in which South Korea moves first; and analyzes each subgame perfect Nash equilibrium according to the flow allocation scenarios. The compensation amount of the additional water that North Korea would provide was calculated, but it was confirmed that this calculated amount alone does not provide sufficient incentive to make North Korea accept the South Korean proposal. Therefore, this paper suggests a plan to jointly implement a new project where the two Koreas can cooperate with each other in the field of water resources instead of simple monetary compensation, and to share the benefits derived therefrom equally. The modernization project of North Korea’s outdated hydroelectric power facilities is suggested as an example of a new cooperation project, and the measures to ensure the South Korea's investment recovery during the implementation process is also taken into account.

In the future, it will be necessary to prepare for the era of cooperation between the two Koreas in the field of water resources by continuing more study based on the game structure of this paper about the diversified models of games; where North Korea becomes the first mover; where the bargaining power between the two Koreas is equal; where a Bayesian equilibrium should be considered because there is an information asymmetry between the two Koreas; and so on.

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