BANKRUPTCY MODEL APPLICATION TO MISSOURI RIVER WATER ALLOCATION

A Thesis
Submitted to the Graduate Faculty
of the
North Dakota State University
of Agriculture and Applied Science

By

Heshani Anjalie Manaweera Manaweera Wickramage

In Partial Fulfillment of the Requirements
for the Degree of
MASTER OF SCIENCE

Major Department:
Agribusiness and Applied Economics

May 2019

Fargo, North Dakota

North Dakota State University
Graduate School

Title

Bankruptcy Model Application to Missouri River Water Allocation

By

Heshani Anjalie Manaweera Manaweera Wickramage

The Supervisory Committee certifies that this ***disquisition*** complies with North Dakota State University's regulations and meets the accepted standards for the degree of

MASTER OF SCIENCE

SUPERVISORY COMMITTEE:

Dr. Robert R. Hearne
Chair

Dr. David C. Roberts

Dr. Jeremy J. Jackson

Dr. Zhulu Lin

Approved:

06/05/2019	Dr. William E. Nganje
Date	Department Chair

ABSTRACT

Growing demand for water and improper resource management over the years have led conflicts among states and countries. This research applies cooperative game theory. The bankruptcy model, where claims for resources exceed their total availability, was applied to Missouri River water allocation during dry years. In this study, five allocation rules were applied. These include Proportional, Constrained Equal Award, Sequential Sharing Rules based Proportional, Mianabadi’s methodology, and a proposed Modified Constrained Equal Award rule in allocating Missouri River water among two agents where their primary purposes were managing the reservoir water level and navigation channel. Selection of the best allocation rule depends on the beneficiaries, and there is no exact method to choose the best. However, this study reveals that the best approaches are proposed Modified Constrained Equal Award and Proportional rules to allocate water among the agents in the Missouri River for dry years.

ACKNOWLEDGEMENTS

I would like to convey my sincere gratitude to my adviser Dr. Robert Hearne and my committee members Dr. David Roberts, Dr. Jeremy Jackson, and Dr. Zhulu lin for continuous support and guidance to complete my Masters' thesis. Moreover, I would like to thank the Department of Agribusiness and Applied Economics, the Center for Regional Climate Studies, NDSU and NSF ND EPSCoR award IIA-1355466 for providing me the financial support in completing the thesis. Further, I would like to express my gratitude to Joel D. Knofczynski, Hydraulic Engineer of Missouri River basin water management of US Army Corps of Engineers for providing me the data for this study and I am grateful for my family, friends and all who contributed their valuable cooperation.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

1. INTRODUCTION

1.1. The Need for the Water Management

Water is a scarce and valuable natural resource (Indiana suggested ordinance, 2007). With global growth in population and income, the demand for the water will continue to increase over the years. The impact of climate change in arid and semi-arid regions of the world, including the United States, will indicate more variable water availability (Durant R.F., 2011). Water is mainly used for irrigation, electricity generation, navigation, human and animal consumption, industrial production and cooling, recreation, and ecosystem maintenance.

As a result of this increasing demand and more variable supply, allocation of shared water resources has become an important geopolitical issue around the world. All over the world, many disputes over international and interstate waters have been reported, and these conflicts have challenged current water management policy. One of the reasons for having interjurisdiction disputes is the use of the principal without considering the type of water use or purpose of water uses. This led to a lack of water needed for some countries or some states for their daily work such as navigation, recreation, and irrigation purposes.

Many of the major rivers in the United States have histories of lengthy, cumbersome court disputes and legal struggles regarding the shared water resources (Dellapenna, 2005a). Not only are the rivers of the arid western United States subject to conflicts, but also the relatively humid eastern states in the United States have begun to experience similar disputes due to increased demand for water and water quality (Abrams, 2002; Dellapenna, 2004, 2005b; Glennon, 2004; Shrek, 2005; Tarlock, 2004). Due to these cumbersome court disputes, the need for proper water management has been identified as an important concern all over the world.

1.2. The Background of Missouri River

The nation's largest river, the Missouri River, flows through semi-arid western Rocky Mountains to the Mississippi River. The Missouri River connects to the Mississippi River at St. Louis, Missouri. The basin includes ten states: Wyoming, Montana, Colorado, Nebraska, Kansas, North Dakota, South Dakota, Minnesota, Iowa, Missouri, and thirty tributaries (Hearne & Prato, 2016). Ninety-five percent of the land around the Missouri River is used for agriculture. The Missouri river basin is known for the adverse climate change effects as it goes through climate extremes, including droughts, floods, long cold winters with storms, and dry and hot summers. Due to the human behavior, the Missouri River and surrounding lands have had to face the challenges of limited water supplies during times of extreme adverse climate. Since the climate is expected to change more adversely in the future, especially during spring and winter periods, causing changes in the temperature and the precipitation will lead to more water variability in the Missouri River. These extreme climate events highlight the necessity of proper water allocation management in the future.

For much of the 19th century, the Missouri River was used as a transit route into the northern Great Plains. The Pick-Sloan dam projects considerably modified the river from its natural state and navigation, hydroelectricity generation, municipal and industrial water supplies, recreation, and ecosystem maintenance.

1.3. River Compacts and Allocation Rules

In the Western United States, interstate river compacts are often used for water allocation among riparian states. Interstate river compacts can be defined as an agreement between states which has been negotiated and agreed to by every participatory state. Once Congress ratifies compact agreements, it becomes federal law and a contract between participatory states. The uses of the interstate river compact are for water allocation, flood control, and river basin planning. River compacts provide feasible rules for the distribution of water. Currently, there are twenty-one river compacts in the United States. These river compacts are either fixed or proportionate river compacts. Fixed river compacts allocate a fixed amount of water to agents in the system while proportionate compacts assign a percentage of available water among states depending on the situation of the water sharing issue. Out of twenty-one river compacts, five use fixed river compacts, eight use proportionate river compacts, and the other eight use a combination of both fixed and percentage river compacts or incorporated other allocation rules. For example, the Colorado River compact is the first ever compact which was established in 1922 among seven states (Bennett et al., 2000). There are two areas in the compact, the upper basin division (Colorado, New Mexico, Utah, and Wyoming) and the lower basin division (Nevada, Arizona, and California), and the river compact is based on annual streamflow water allocations while other river compacts in the western United States might be based on seasonally or daily claim requirements. The objective of a river compact is to store excess water from the spring runoff and allocate the water to users during summer periods. Large-scale reservoirs can also provide water during drought periods when the demand is high. The river compacts will support institutions to monitor effectively, and it will take necessary actions to minimize vulnerability due to extreme weather events, which will comply with the agreed-upon rules.

Unlike other major rivers such as the Colorado, Rio Grande, and the Susquehanna, there is no interstate river compact in the Missouri river. Due to the absence of a river compact, the US Army Corps of Engineers (USACE) became the *de facto* river master of the Missouri river. The federal government must allocate water between upper basin water users and lower basin water users. Failure to allocate water to the upper and lower water basin users according to their claims results in conflicts between states and different water users which have led to cumbersome court disputes. Therefore, it is essential to provide research to support the development of cooperative water management.

Cooperative game theory (CGT) provides tools that can be used to identify rules for the development of interstate river compacts. CGT provides the evaluation for the sharing rules of an asset when the asset can't divide among the users in the system. The other reason for using CGT to address the water allocation issues is that methodology is simple, and policymakers and agents can apply it easily. In the game theory, CGT is defined as a game that has a group of players ("coalitions") who compete over an asset and would establish agreements among themselves to obtain maximum utilization of the asset. It summarizes the total coalitions that will form in the system, the collaborative actions that users can take to maximize utility, and the resulting collective payoffs. One tool of the CGT that can be used to develop the interstate river compact is bankruptcy model.

1.4. Problem Statement and Research Approach

Water scarcity is an issue that is having an impact on a large proportion of the world's populations, and many countries are already facing the problem (Houba et al. 2014; Mekonnen and Hoekstra 2016; Saz-Salazar et al. 2016). With the adverse change of climate event in future water, scarcity will be a huge issue all over the world. Therefore, proper river water management is a must. The water sharing problem during water scarcity is similar to the bankruptcy model (Dagmawi Mulugeta Degefu et al. 2016). The bankruptcy problem is an economic concept where the amount of divisible resource available for sharing is less than the resource demanded (O'Neill, 1982). This study applies the bankruptcy model to Missouri River water management.

The study takes into account both the Missouri river basin states as well as the pertinent economic sectors as claimants when developing the bankruptcy model.

1.5. Research Objectives

The main objective of this study is to apply the bankruptcy model to explore how eclectic claims to an asset can be distributed when the asset is not sufficient to satisfy all agents requested claims.

Specific objectives of this paper can identified as follow;

1. Identify the allocation rules that have been used in shared water resources in previous literature
2. Determine which bankruptcy model approach would be best fitted for the Missouri River case study, and
3. Describe the potential barriers and challenges to the model

1.6. Organization of the paper

Following this introduction, the second chapter of this thesis presents how previous scholars have approached the shared water issues, what models they used, what are the best models and the research gap that need to address. In chapter three the theoretical and empirical methodology is presented. The fourth chapter discussed the research results which was then followed by the conclusions of this study in chapter five.

2. LITERATURE REVIEW

2.1. Water River Governance

Natural Resource Management can be identified as the wise manipulation of natural systems which produce resources to utilize their long-term production in a way to benefit both human and biological production, and this management is a decision-making process (Hooper, B.P., 2011). The author O'Riordan in 1997, introduced natural resource management as a decision-making process, as it allocates resources according to society's need, desires, political and social institutions, and arrangements of legal and administrations. The way that people utilize water and land is used to determine natural resource management (Hooper, B.P., 2011). Therefore, to meet the evolving needs and demands of society, water management agencies have evolved along with the community over time. Multipurpose agencies and management authorities had developed when the infrastructure became more complex, with multiple outputs and beneficiaries (North, 1990; Saleth & Dinar, 2004; Hearne, 2007). Some states' water has been managed under state laws which were adapted from English common law (Hearne & Prato, 2016). The prior appropriation law, used in most western United States, recognizes the "first in time, first in the right" principle, while it does not consider the type of water use, for an instance whether it's for consumptive, irrigation, and agricultural use, etc. and allocates water to the users who put water to beneficial use first before users who established water rights later (The Missouri River Ecosystem: Exploring the Prospects for Recovery, 2002). Since the 1870s, Western water law evolved to address the conflicts among states and each state has its law. As a result, well-regulated market transactions and water-use rights were established (Josephson, 1987; Hobbs, 2004).

The US constitution gave jurisdiction to the federal government over interstate commerce (Hearne & Prato, 2016). As the only engineering expertise in the federal government, US Army Corps of Engineers (USACE) constructed harbor facilities, fortified, dredged, and cleared the waterways. The USACE is responsible for flood control, navigation, and ecosystem restoration activities in the Missouri River. The USACE started operating multi-purpose reservoirs when the federal government granted the responsibility for the flood control in 1936 using Flood Control Act (Hearne & Prato, 2016). Before the authority of western states established the federal government involvement water rights. The Bureau of Reclamation (BuRec) constructed and operated large dams before the Pick-Sloan plan was implemented (Bureau of Reclamation History of Program, 2011). The Pick-Sloan plan for the Missouri River and tributary dams represented a merger between a USACE plan to build main stem dams and lower river levees to provide navigation from the Mississippi River to Sioux City, Iowa and a more ambitious BuRec plan that included 90 water storage, conduction, irrigation, and hydroelectric generation projects (Hearne & Prato, 2016). Despite the increased capacity to control the river, the debate over the Missouri River water allocation between upper and lower basin states continues.

2.2. River Compacts

A river compact is an agreement between more than one states in which each party has agreed on a procedure to allocate water among themselves. This procedure mainly addresses conflicts between the states to avoid lengthy and cumbersome court disputes. The previous literature has examined different scenarios involved in river compacts. Several important conclusions have been drawn from a study by Bennett et al. (2000) which accessed two different compact types: fixed amount allocation type and allocation based on the percentage of available water to the riparian states. The authors argue that even though fixed and percentage compacts are in practice, the optimal design of the river compact is the combination of both types. The main objective of the study was to identify the main drivers for the determination of the economic-efficiency and risk sharing characteristics for different kinds of river compacts in the Western United States. The study revealed that the efficiency of a compact type is based on the benefit functions of the upper and lower basins and the distribution of streamflow. Furthermore, the authors found that the main factors that drive compact efficiency are upper basin and lower basin net benefits, distribution type, mean, and variance of the flow.

Some of the previous literature has defined compacts as rigid structures due to their incapability to adapt to changing environments, as well as their inability to be regulated by direct water users. Schlager & Heikkila (2009) examined this claim by studying fourteen Western Interstate river compacts. Their study was the first empirical examination of the capability of the interstate river compacts to provide solutions to state conflicts. The results showed that even though populations expect the river compacts to be deficient in resolving these conflicts, surprisingly they have solved a variety of state conflicts, especially Zero-sum distributional conflicts. Therefore, the study found that unanimity rules don't act as high decision-making barriers for state conflicts. Moreover, this study provides policy options for transboundary river compacts in the Western United States, such as improvement of compliance mechanisms. The study also suggested further research applying their IAD framework to interstate conflicts in transboundary basins to minimize the interstate compact conflicts.

2.3. Cooperative Game Theory

Cooperative game theory (CGT) can be used to address water allocation issues. Bankruptcy Game (BG) techniques are a part of CGT that can be used to analyze water allocation problems (Young, 1994). A classic BG model is used when the agents claim to divide the available estate. Therefore, each agent would be able to receive a non-negative amount which doesn't exceed its claim.

Sechi & Zucca's (2015) study in the Mediterranean region examined the BG approach to address water resource allocations in critical scarcity conditions and developed a methodology linked to BG techniques and CGT. The method allowed them to evaluate the sharing rules when there were not sufficient resources for the demand of the users in the system. The methodology was developed with consideration of the priorities of water allocation denoted by the users' willingness to pay. The method provides a useful tool in decision making in cooperated bankruptcy rules, such as Proportional rule (PRO), Constrained Equal Award rule (CEA), Constrained Equal Loss rule (CEL), the Talmudic rule (TAL), and the Adjusted Proportional rule (APROP).

Madani et al. in 2014 have proposed a novel bankruptcy approach as the irregular spatial water distribution across the riparian states' river basins in Iran. The allocation solution of the novel BG approaches provided non-linear optimization solutions. The four bankruptcy allocation rules that authors developed and examined were PRO, APROP, CEA, and CEL. To evaluate the acceptability and stability of the bankruptcy allocation solution Madani et al. introduced Bankruptcy Allocation Stability Index (BASI) in 2014. BASI is the modified version of Bankruptcy Power Index (BPI). BPI is used to evaluate the best allocation approach which players of the system would agree when the claim exceeds the available resources. BPI was introduced by Shapley and Shubik in 1954. Higher the BPI value, higher the willingness of players to cooperate and the stability of the approach is high as well. Since the variable, non-cooperative gain of the player of the BPI equation is zero in cooperative bankruptcy models the scholars developed and modified the BPI, which is BASI. The higher the BASI value the stability and acceptability of the allocation solution is lesser (Madani et al., 2014).

The need for an effective institutional arrangement to avoid new diversions of water from Great Lakes has been a significant issue to address this concern Becker and Easter (1997) have done a study to identify the 'economically desirable diversions' and how institutional arrangements should be formed for this problem. They argued that Game theory plays an essential role by determining the formation of coalitions to achieve cooperative agreements. Hurwicz (1973) suggested that non-cooperative game theory has a considerable disadvantage to cooperative game theory, due to the inability of interactions among players and outcomes that are either pure coalition or pure conflict. Under the study done by Becker & Easter (1997) results have shown that the cooperative solution has much smaller diversion than the uncooperative solutions. Furthermore, the authors argued that it is necessary to have a "core" to exist a "win-win" game. Findings of the study show that all players won't have a positive net gain even under the Nucleolus stating that there was always an issue when the benefits were divided from an open-access water resource such as the Great Lakes (Becker, N. & Easter, K.W., 1997).

Conflicts over international water are mainly due to the absence of proper accepted allocation mechanism for the division of water resources or their benefits (Wolf, 1998). The principle that takes account for this issue is "equitable and reasonable utilization." The International Law Association (ILA) in 1966, indicated that the majority of nations uses the Helsinki rules when players use water from International water sources.

Previous scholars (Gachter & Riedl, 2006; Herrero et al., 2009; Xia & Cui, 2009) have done practical studies using three rules based on the BG: PRO, CEL and CEA due to equal proportions of claims, equal losses and equal awards respectively (Mianabadi et al., 2014). Mianabadi et al. (2014) introduced a new bankruptcy rule in cooperating agents' contribution to total resources and to the claims which align with the UN Watercourses Convention of 1997. They have applied bankruptcy rules to the Euphrates River and they concluded that comparing and analyzing the PRO, the CEA, and the CEL allocation rules do not follow in many states of the study as the "equitable and reasonable utilization" principle does not take in part in the total supply flow, which will then lead to conflicts.

The necessity of Missouri River water management has evolved since the beginning of the Pick-Sloan reservoir system (Hearne & Prato, 2016). Shafer et al. in 2014 mentioned that basin of the Missouri river is always affected by the climate extremes as it experiences prolonged droughts, periodic floods, cold winters with frequent storms, and hot and dry summer and is expected to increase in future periods. According to Hearne and Prato (2016), the nation's most economically grazing, and croplands are located in the basin and due to the absence of river compact guiding in the Missouri River, the economic contribution from large irrigation projects has been decreased during last 70 years. Since the USACE remains the *de facto* river master in the Missouri River, the need of its reservoir's protocol collaboration with other federal agencies such as the FWS, EPA, BuRec and WAPA and the states are highlighted by the authors in the study. Moreover, the authors concluded that the dam system provides a valuable service by controlling flood with extreme climate change. Therefore, an interstate river compact is necessary to protect the economic value of the Missouri River.

3. METHODOLOGY

3.1. What is Game Theory?

In 1944, game theory was introduced by Von Neumann and Morgenstern when they published "Theory of Games and Economic Behavior." A game theoretical analysis is used to model the interactions among players when optimal agent behavior depends upon the behavior of others. Game theory provides a solution for each player involved in the system rather than its overall objective. Players tend to weigh their objective satisfaction and cannot assume that they will act to achieve the system objective only (Madani, K., 2010). This methodology is used for other environmental and social issues, but it is novel to water resource issues and different from other conventional methods.

Game theory can be branched into two sections. They are Cooperative Game Theory (CGT) and Non-Cooperative Game Theory (NCGT). The main difference between CGT and NCGT is that CGT presents how players compete and cooperate to capture their goals and thus can be called "coalitional" while NCGT is "procedural." In NCGT each agent considers all the information that is available to them to capture their goals in a defined procedure (Chatain O., 2016). Nevertheless, in both cases, players consider their objectives.

3.2. Bankruptcy Model Application for Water Allocation

The main two reasons for selection of bankruptcy rules for the water allocation issue are;

(i) It follows the real bankruptcy problems as their claims exceed the available resources, and

(ii) The rules are simple and can be used easily by agents and policymakers (Ansink and Weikard, 2012)

For water allocation, the application of bankruptcy rules is different from the general application of bankruptcy rules due to the geographical positions of the players, and it is characterized by the players' claims and contributions to the asset. In the river sharing case, the asset is water. Therefore, bankruptcy rules play an important role to address the water allocation issues not only for Missouri River but also for other water resources.

3.3. Theoretical Background

In this study, five approaches are analyzed to determine the best solution for the Missouri River water allocation issue. Five strategies are namely:

i. Proportional Rule (PRO) based on the Sequential Sharing Rules (SSRs)
ii. Mianabadi H. et al.'s (2014) methodology
iii. Proportional Rule (PRO)
iv. Constrained Equal Award Rule (CEA), and
v. Proposed modified CEA rule.

Five of these methods used bankruptcy model approach to address the water sharing issues.

The essential variables introduced in the classic bankruptcy methodology are:

1. The set of agents ($N \geq 2$)
2. The asset (E)
3. The claims (C_i)
4. The contribution of agents to the asset (a_i)

Considering the variables mentioned above, the bankruptcy problem can be defined as a function of the asset (E), the number of agents (N), agent's claims (C_i), and their contribution to the asset (a_i). The objective of the bankruptcy model is to provide a solution to the water allocation issue, which is to determine each agent's water allocation (x_i) when

$F(N, E, C_i, a_i) = x_i$ and the distribution of water shouldn't be negative ($x_i \geq 0$).

In river sharing issue, the contribution of all agents to the asset and agent's claims markup total asset (E) and total claims (C). These relationships can be shown in mathematically as equation (1) and (2) respectively. Equation (3) presents that the allocated resources shouldn't exceed the agent's contribution to the asset and equation (4) displays that any agent should not receive a negative allocation.

$$E = \sum_{i=1}^{n} a_i \tag{1}$$

$$C = \sum_{i=1}^{n} c_i \tag{2}$$

$$\sum_{i=1}^{n} a_i = \sum_{i=1}^{n} x_i \tag{3}$$

$$0 \leq x_i \leq c_i \tag{4}$$

3.3.1. First Approach: SSR with Proportional Rules Application

The first approach that consider in this study is the Sequential Sharing Rule (SSRs) with the Proportional Rule (PRO). SSR was first introduced and developed by Ansink (2009). SSR rule can be applied only if agents in the particular water allocation issue are linearly ordered. Moreover, compared to other classical bankruptcy rules this approach considers the agent's contribution to the asset as well. The agents' contribution $a_i \geq 0$; is "the proportion of total inflow of river which originates in the territory of each agent" (Ansink and Weikard, 2012).

Ansink and Weikard (2012) have introduced some new definitions and equations to develop this approach. They are;

- The total available water of the agent i (E_i) is the sum of the river inflow on the territory of i and any unallocated upstream water

$$E_i = a_i + \sum_{j \in U_i}(a_j - x_j) \quad (5)$$

- The excess claim of the downstream agent i (C_D) is the sum of claims net of assets of all agents downstream of i

$$C_D = \sum_{j \in D_i}(c_j - a_j) \quad (6)$$

Each agent's allocation can be calculated from the following equations, based on the definitions mentioned above. The allocation coefficient of the agent *i* can be obtained from equation (7).

$$\lambda_i = \frac{E_i}{C_i + C_D} \quad (7)$$

and

$$x_i = \lambda_i . c_i. \quad (8)$$

3.3.2. Second Approach

This novel methodology was introduced by Mianabadi, H.et al. (2014). The variables that considered in this approach are;

1. The total deficit which is the difference between the claims and the assets

$$D = C - E \quad (9)$$

2. The rate of contribution ($a_i/\Sigma a_i$)
3. The rate of the claim ($c_i/ \Sigma c_i$)

The concept of the methodology is to divide the total deficit by the rate of contribution and claims and subtract the loss for each agent (d_i) from their claim (Mianabadi, H. et al., 2014).

d_i can be calculated as follows:

$$d_i = \frac{\left(\frac{c_i}{\sum_{i=1}^{n} c_i} + 1 - \frac{a_i}{\sum_{i=1}^{n} a_i}\right)}{n} * D \quad (10)$$

and

$$x_i = c_i - d_i;\ 0 \leq x_i. \quad (11)$$

The main principle behind this approach is that agents who have a higher contribution rate and a lower rate of claims would be allocated relatively more.

3.3.3. Third Approach - The Proportional Rule

The proportional rule assigns claim equally to all players/agents. Therefore, the proportion of agent i can be shown mathematically below:

$$P_i = \frac{X_i}{C_i} = \beta \quad (12)$$

According to Madani et al. (2014), the equal proportion can be obtained by dividing the total asset by total claim, which emphasizes that the equal proportion (P_i) is equal to the variable β introduced in the equation 13. Then that proportion is multiplied by agent i's claim. The definition of the proportional rule can be defined mathematically as follows:

$$X_i^{PRO} = \beta C_i \text{ where } \beta = \frac{E}{C} \quad (13)$$

3.3.4. Fourth Approach – Constrained Equal Award Rule (CEA)

CEA rule was followed by rabbinical legislators (Dagan and Volij, 1993; Madani et al., 2014). The concept of the CEA rule is to share the asset equally subject not to exceed each agent's claim. Each agent is initially assigned the amount of the asset of the lowest claimant. If sufficient assets are remaining the claim of the second lowest claimant is distributed to all but the lowest claimant. This continues until the asset is exhausted. As a result, any agent won't receive any excess amount other than their claim. The mathematical formulation of this rule as follows:

$$X_i^{CEA} = \min(\Pi, Ci) \text{ where } \sum_{i \in N} \min(\Pi, C_i) = E \quad (14)$$

3.3.5. Fifth Approach – Proposed Modified CEA Rule

This approached is proposed for this study as agents' claims are much higher than the total available water. Since the CEA rule gives priority to the lowest claim of the agents and the claim is almost ten times greater than the total available water distributing the claims among two agents in this study is challenging. As a result, the lowest claim agent and the other agent's claim will not be satisfied at all. To address this shortcoming, this study proposed the modified CEA rule proposes to consider the claim rate percentages. Therefore, instead of considering the lowest claim, this novel methodology will consider the lowest claim rate. Initially, the lowest claim rate will be satisfied by allocating the lowest claim percentage of the total available water among the agents, and all other unmet claim rates will be satisfied with the remaining water resources. A percentage of the claim rate will be obtained by dividing the agent's claim by total claim then multiplied by a hundred. This can be shown mathematically as follows:

$$\text{Percentage of claim rate of agent i } (C_a) = \frac{C_i}{\sum_{i=1}^{n} C_i} * 100 \tag{15}$$

After obtaining the lowest claim percentage, that percentage is multiplied by the total available water. Then the resulting allocation will be distributed among the agents. The initial allocation of water among agents can be obtained using the following mathematical formula.

$$\text{Initial water allocation } (X_i) = \text{Total available water } (E) * C_a \tag{16}$$

Once the lowest claim agent is fully satisfied, the process will continue until all agents were satisfied.

3.4. Study Area

The Missouri River originates in Southwestern Montana and flows in a southeasterly direction about 2,315 miles to join the Mississippi River approximately 15 miles upstream of St. Louis, Missouri (US Army Corps of Engineers, 2019). The Missouri River is the nation's longest river. For many decades people have depended on the Missouri River for agricultural purposes, recreation, and transportation, etc. In this study as the upstream agent, the reservoir system is considered while the navigation system recognized as the downstream agent.

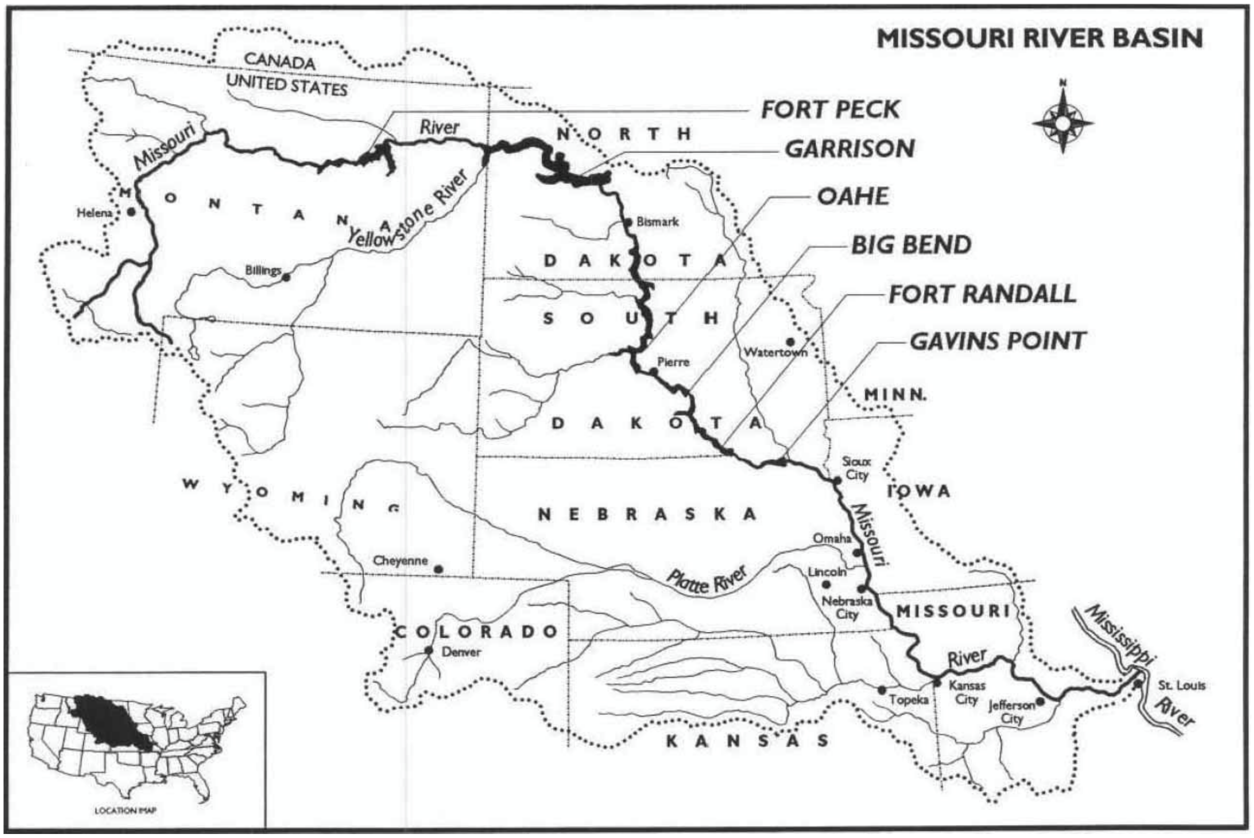


Figure 1. Map of dams of Missouri River Basin. *Source:* Hearne and Prato (2016)

3.4.1. Navigation Channel

Navigation of the Missouri River starts at Sioux City, Iowa and flows to the confluence with the Mississippi River near St. Louis, Missouri. The navigation channel supports barge freight transportation. The USACE releases the water from storage reservoirs to support the navigation from late March or 1st of April to 1st of December. Iowa, Nebraska, Kansas, Missouri, and South Dakota are the main five states that the navigation channel serve. The upper three reservoirs are the largest. Fort Peck, Garrison, and Oahe dams provide almost eighty-eight percent of total water storage capacity to the navigation channel (The Missouri River Ecosystem: Exploring the prospects for Recovery, 2002).

The USACE has the authority over the navigation channel where they construct, maintain the Missouri River water release for flood control, navigation, and other purposes. Due to irregular dry and wet periods, barge navigation was affected during the last decades. The main objective of the USACE is to manage the six reservoir levels in the upper stream to maintain the navigation channel (Schmeidler, 1969; Lund, 1996). The advantage of maintaining the navigation channel is that it provides support to barge transportation. Efficient barge transportation requires the appropriate water level in the downstream navigation channel.

3.4.2. Reservoir System

There are six major multipurpose dams which have been built and are managed by the USACE. They are Garrison, Oahe, Big Bend, Fort Randall, and Gavins Point. These six USACE reservoirs contain about 73.4 million acre-feet of storage capacity, which is the most extensive reservoir system in the United States. This system provides the supports for the flood control for over 2 million acres of land, and also at normal pool levels, provide water surface area for recreation, fish, and wildlife enhancement (Master manual of Missouri River, 2006).

3.5. Data Sources

In this study, eight main variables were used to obtain the water allocation for the players. These variables are a total deficit of each agent, total claim, each agent's claim, number of agents/players, each agent's contribution to the asset, total assets, total available water for each agent, and excess downstream claim of the agent ***i***. Only two agents were considered in this case study and to obtain their claims primary data were used. For the upstream agent, the excess downstream claim was the total system storage difference between a wet year and dry year. The data for the total system storage for the period 1997 to 2017 were obtained from the USACE Northwestern Division - summary of actual regulations of Missouri River mainstem reservoir system. For the downstream agent's excess downstream claim, the primary data for the daily water release from Gavins Point for the dry and wet years for the period of 1980 to 2017 were provided by Joel D. Knofczynski, Hydraulic Engineer of Missouri River basin water management of USACE. The data for total available water for the upstream agent was also retrieved from the total system storage, which was published by the USACE, and the primary data for the total available water for the downstream agent were obtained from USGS database. The data of the claim of the upstream agent which is the total system storage of carryover multiple uses was obtained from USACE Northwestern division Missouri River water management division for the year 2017. The claim of the downstream agent, which is the daily water release from Gavins Point for the wet years also provided by Joel D. Knofczynski, Hydraulic Engineer of Missouri River basin water management of USACE. In summary, primary data of this study were gathered from the USACE and USGS database to calculate the water allocated for the agents.

3.6. Missouri River Case Study

Ten states serve the Missouri River basin, and each of these ten states have their objectives and their claims. Some of these states have a claim based upon riparian water rights. The federal government does not allocate water for states as they have state water law. However, because of low population density, and soils not suited for surface irrigation, some upper basin states have not fully allocated all of the water that is available to them. Since key upper basin states feel that they are still owed water and because of added pressure to maintain ecosystems under the Endangered Species Act conflicts between upper and lower basin states and conflicts between consumptive and instream uses have increased (Hearne and Prato, 2016).

In game theory, the fundamental element is a player which can be identified as an individual or a group of individuals. In this case study, only two purposes were considered, and they are managing reservoirs for multipurpose use upstream or the navigation channel for barge transportation downstream. These are the two “players” in the game.

In accordance with these two purposes, the ten states of the Missouri River basin can be divided into two players. Nebraska, Kansas, Iowa, and Missouri are identified as downstream agents, and those states are linearly ordered in the downstream of the six-reservoir system which has identified as the upstream agent. South Dakota, North Dakota, and Montana are recognized as an upstream agent as their primary purpose of water is to maintain water level for recreation. Wyoming, Colorado, and Minnesota are upper basin states but far removed from the mainstem. Although southeast South Dakota may benefit from barge navigation because of proximity to the barge channel in Sioux City Iowa, it is assumed that most benefits come from the use of the four reservoirs within the state. The claim for the upper stream agent is recognized as management of reservoir level while the management of the navigation channel is the claim of the downstream agent. Considering the facts mentioned above, the five models were used to calculate the water allocation for those upper and downstream agents.

This case study mainly focuses on the dry years as it affects the navigation channel and reservoir levels. Improved navigation channel always beneficial to the activities of USACE. During the dry years, barge transportation has declined drastically resulting in conflicts between upper and lower basin. Deep navigation channel from Sioux City, Iowa has been considered as a boom of transportation of export agricultural commodities (Hearne and Prato, 2016). Therefore, the continuous channel is necessary during the operation period which is from the 23rd of March to 22nd of November (Guhin, 1985; Hearne and Prato, 2016). During the dry years, the navigation period was 198 or 205 days which is less than 245 standard navigation period. This results in the interruption to the transportation and conflicts between states. That is why the end of the navigation period in dry years plays a crucial role and, in this study, this period is explored.

3.6.1. Approach One: SSR based PRO method

3.6.1.1. For Upstream agent

The total available water of the upstream agent can be considered as, the difference between the total system storage of carryover multiple uses and permanent pool levels which is maintained for an assumed eight-year dry period. Since the USACE has to maintain the permanent pool level during wet and dry years, the difference between carryover multiple uses and permanent pool level is the available water storage for the upstream agent which can be used for their daily uses and their claims during the dry period. Therefore, the total available water (E_U) of the upstream agent can be calculated as follows:

$$E_U = \frac{(56.1-17.6)}{8} * \frac{(245-198)}{245} = 4.8125*0.1918 = 0.9230 \text{ MAF} \tag{17}$$

The excess downstream claim of the upstream agent (C_D) is the amount of water that is needed to maintain the full navigation for the full year. Considering the navigation period from 1997 to 2017, wet years are 1997-2003 and 2009-2017 while 2004-2008 are dry years. The wet year can be defined as the full navigation period which is eight months (245 days). The dry year is the year that had the lowest navigation days (between 198 to 205 days). According to the data C_D can be calculated as follows:

- Calculations for total system storage for wet years

Table 1

Total system storage for the wet years of the Missouri River

Year	Date	Total system storage (MAF)
1997	1st of September	69.1
1998	1st of September	61.8
1999	1st of September	63.7
2000	1st of September	54.4
2002	30th of September	45.5
2003	30th of September	41.4
2009	30th of September	55.9
2008	30th of September	44.5
2010	30th of September	62.1
2012	1st of September	54.3
2013	1st of September	52.1
2014	30th of September	60.0
2015	1st of September	60.3
2016	1st of September	58.1
2017	1st of September	60.4
Average:		56.24

Units: Million Acre Feet (MAF)
Source: US Army Corps of Engineers, Northwestern Division Regulations, 1997-2017

- Calculations for total system storage for dry years

Table 2

Total system storage for the dry years of Missouri River

Year	Date	Total system storage (MAF)
2004	30th of September	35.8
2005	30th of September	36.2
2006	30th of September	35.0
2007	30th of September	37.4

Units: Million Acre Feet (MAF).
Source: US Army Corps of Engineers, Northwestern Division Regulations, 2004-2008.

C_D for the upstream agent can be obtained using the following mathematical formula:

Excess claim (C_D) = Average total system storage (wet years) – total system storage (dry year)

Since this case study considers the dry years' calculations for four dry years were obtained separately as table 3.

Table 3

Excess claim for the dry years of Missouri River for the upstream agent

Year	Calculations	Excess claim (CD)
2004	56.24 – 35.8	20.6
2005	56.24 – 36.2	20.04
2006	56.24 – 35.0	21.24
2007	56.24 – 37.4	18.84

Units: Million Acre Feet (MAF).

- Claim (C_i) of the upstream agent is 56.1 MAF which is total system storage.

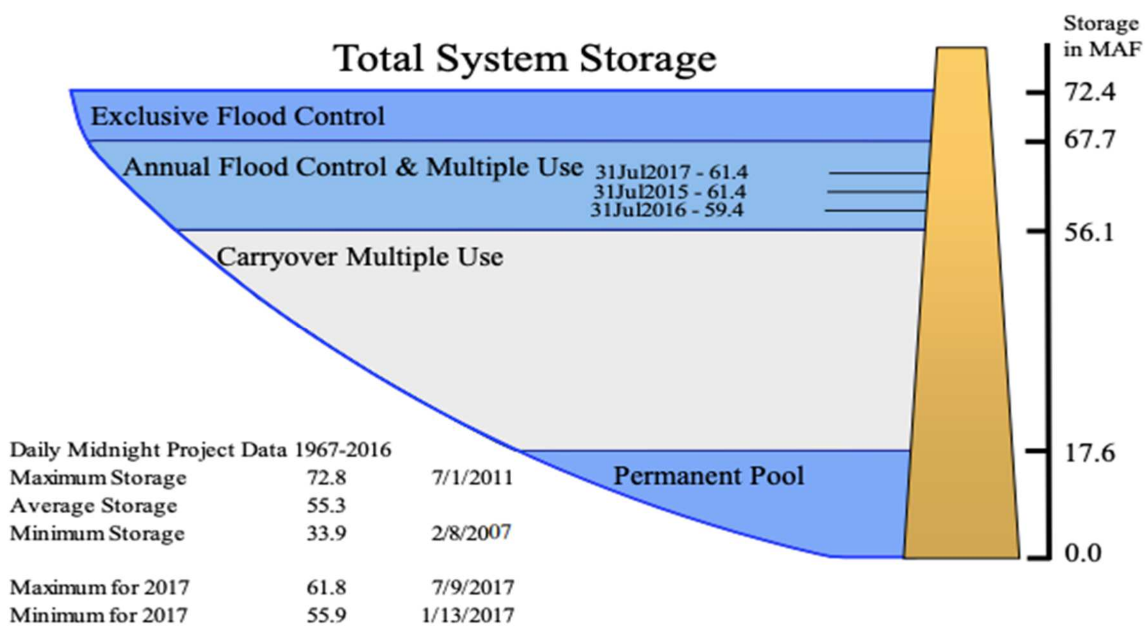


Figure 2. Total system storage of Missouri River, end of July 2017. *Source*: US Army Corps of Engineers, Northwestern Division, 2017. Unit is in Million Acre Feet (MAF).

Fifty-six and one-tenth MAF was used as the upstream agent's claim because it represents the total level of water that upstream water users would like to have at the end of the navigation season. Additional storage above 56.1 MAF is used for flood control and seasonal storage purposes.

Using C_i, E_U, and C_D variable the allocation coefficient (λ_i) and allocation for the upstream agent (X_i) for the dry years can be calculated as below.

First dry year (2004):

$$\lambda_i = \frac{0.9230\ MAF}{56.1\ MAF + 20.6\ MAF} = \frac{0.9230\ MAF}{76.7\ MAF} = 0.012 \tag{18}$$

$$X_i = 56.1 \text{ MAF} * 0.012 = 0.6732 \text{ MAF} \tag{19}$$

Second dry year (2005):

$$\lambda_i = \frac{0.9230\ MAF}{56.1\ MAF + 20.04\ MAF} = \frac{0.9230\ MAF}{76.5\ MAF} = 0.012 \tag{20}$$

$$X_i = 56.1 \text{ MAF} * 0.012 = 0.6732 \text{ MAF} \tag{21}$$

Third dry year (2006):

$$\lambda_i = \frac{0.9230\ MAF}{56.1\ MAF + 21.24\ MAF} = \frac{0.9230\ MAF}{77.34\ MAF} = 0.0119 \approx 0.012 \tag{22}$$

$$X_i = 56.1 \text{ MAF} * 0.012 = 0.6732 \text{ MAF} \tag{23}$$

Fourth dry year (2007):

$$\lambda_i = \frac{0.9230\ MAF}{56.1\ MAF + 18.84\ MAF} = \frac{0.9230\ MAF}{74.94\ MAF} = 0.0123 \approx 0.012 \tag{24}$$

$$X_i = 56.1 \text{ MAF} * 0.012 = 0.6732 \text{ MAF} \tag{25}$$

Therefore, the allocation of water for the upstream agent for years 2004, 2005, 2006, and 2007 are 0.6732 MAF.

3.6.1.2. For Downstream Agent

The total available water of the downstream agent can be calculated using water release from Gavins Point plus river inflow from James and Big Sioux rivers plus any unallocated water from the upstream agent. The reason for only consideration of the water release from Gavins Point is that it is the main point that water release for the navigation channel for the downstream agent. The calculations can be shown as follows:

Table 4

Total available water for the downstream agent for dry years (2004-2007)

Year	Average water release from Gains Point/ cfs	Average water release from Big Sioux River/ cfs	Average water release from James River/ cfs	Unallocated upstream water/ MAF	Available water (E_D)/ MAF
2004	10,786	890.13	402.5	0.2498	1.3741
2005	10,238	1,728.94	121.18	0.2498	1.3767
2006	11,549	630.53	88.1	0.2498	1.3934
2007	9,762	2,779.5	98.09	0.2498	1.4281

Sources: USGS and USACE database
Units: Cubic feet per second (cfs) and Million Acre Feet (MAF)

The excess downstream claim of the downstream agent (C_D) is what downstream agent receive from Gavins Point in wet years that they do not receive in dry years. It is the unmet claim for downstream which is the claim in dry periods. This can be written in an equation as follows:

C_D = water flows at Gavins Point to maintain the full navigation – water that actually flows

Table 5

Summary of the number of days of navigation period (dry years)

Year	Start Date	End Date	Number of days of navigation
2004	23rd of March	6th of October	198
2005	23rd of March	6th of October	198
2006	23rd of March	6th of October	198
2007	23rd of March	13th of October	205

Source: www.nwd-mr.usace.aarmy.mil/rcc/tenmost/tenmosthll.html (accessed on February 5th, 2019)

Table 6

Gavins Pont water releases before and after no navigation for dry years

Year	Before	Gavins Point release/ cfs	After	Gavins Point release/ cfs
2004	30Sep2004	23000	07Oct2004	20000
	01Oct2004	23500	08Oct2004	17000
	02Oct2004	23500	09Oct2004	14000
	03Oct2004	23500	10Oct2004	12000
	04Oct2004	23500	11Oct2004	12000
	05Oct2004	23500	12Oct2004	12000
	06Oct2004	22700	13Oct2004	12000
Average		23314	Average	14143
2005	30Sep2005	22000	07Oct2005	17000
	01Oct2005	23000	08Oct2005	14000
	02Oct2005	23500	09Oct2005	11000
	03Oct2005	24000	10Oct2005	10000
	04Oct2005	24000	11Oct2005	10000
	05Oct2005	23000	12Oct2005	10000
	06Oct2005	20000	13Oct2005	10000
Average		22786	Average	11714
2006	30Sep2006	24800	07Oct2006	25000
	01Oct2006	24500	08Oct2006	23500
	02Oct2006	24800	09Oct2006	20500
	03Oct2006	25000	10Oct2006	17500
	04Oct2006	25000	11Oct2006	14500
	05Oct2006	25000	12Oct2006	11500
	06Oct2006	25000	13Oct2006	10000
Average		24871	Average	17500
2007	07Oct2007	20500	14Oct2007	18000
	08Oct2007	19700	15Oct2007	17500
	09Oct2007	18500	16Oct2007	16000
	10Oct2007	18000	17Oct2007	13500
	11Oct2007	18000	18Oct2007	10500
	12Oct2007	18000	19Oct2007	9000
	13Oct2007	18000	20Oct2007	9000
Average		18671	Average	13357

Source: Joel D. Knofczynski P.E., Hydraulic Engineer, Missouri River Water Management, USACE. Retrieved on January 28, 2019.

The calculations for the excess downstream claim of the agent can be shown as follows:

- Year 2004: No navigation as of 6th of October

C_D = water that flows before 10/15 – water that flows after 10/15

Average daily water release from 10/8 to 10/15 = 23314 cfs

Average daily water release from 10/16 to 10/22 = 14143 cfs

Therefore, C_D = 23,314 cfs – 14,143 cfs = 9,171 cfs = 0.127 MAF

- Year 2005: No navigation as of 6th of October

C_D = water that flows before 10/6 – water that flows after 10/6

Average daily water release from 09/30 to 10/6 = 22,786 cfs

Average daily water release from 10/7 to 10/13 = 11,714 cfs

Therefore, C_D = 22,786 cfs – 11,714 cfs = 11,072 cfs = 0.154 MAF

- Year 2006: No navigation as of 6th of October

C_D = water that flows before 10/6 – water that flows after 10/6

Average daily water release from 09/30 to 10/6 = 24,871 cfs

Average daily water release from 10/7 to 10/13 = 17,500 cfs

Therefore, C_D = 24,871 cfs – 17,500 cfs = 7,371 cfs = 0.102 MAF

- Year 2007: No navigation as of 6th of October

C_D = water that flows before 10/6 – water that flows after 10/6

Average daily water release from 09/30 to 10/6 = 18,671 cfs

Average daily water release from 10/7 to 10/13 = 13,357 cfs

Therefore, C_D = 18,671 cfs – 13,357 cfs = 5,314 cfs = 0.074 MAF

The claim of the downstream agent is the navigation days. Since the period considered in this study was 1997 to 2017, the average daily release from Gavins Point for navigation during wet years 1997-2003 and 2009-2017 were considered. The main reason is that during wet years there is enough water release for barge transport without any interruptions. The navigation period is from the 23rd of March to the 22nd of November. Therefore, to calculate the claim only the period as mentioned earlier was considered for wet years.

- C_i = Average daily water release from Gavins Point during navigation period in the wet years = 33,172 cfs = 702,184,896,000 cf = 16.119 MAF

Using the variables E_D, C_i, and C_D the allocation of water to the downstream agent for dry years can be calculated as below.

For first dry year (2004):

$$\lambda_i = \frac{1.3741\ MAF}{0.127\ MAF + 16.119\ MAF} = \frac{1.3741\ MAF}{16.246\ MAF} = 0.084 \approx 0.08 \tag{26}$$

$$X_i = 16.119\ \text{MAF} * 0.08 = 1.2895\ \text{MAF} \tag{27}$$

For the second dry year (2005):

$$\lambda_i = \frac{1.3767\ MAF}{0.154\ MAF + 16.119\ MAF} = \frac{1.3767\ MAF}{16.273\ MAF} = 0.084 \approx 0.08 \tag{28}$$

$$X_i = 16.119\ \text{MAF} * 0.08 = 1.2895\ \text{MAF} \tag{29}$$

For the third dry year (2006):

$$\lambda_i = \frac{1.3934\ MAF}{0.102\ MAF + 16.119\ MAF} = \frac{1.3934\ MAF}{16.221\ MAF} = 0.085 \approx 0.09 \tag{30}$$

$$X_i = 16.119\ \text{MAF} * 0.09 = 1.4507\ \text{MAF} \tag{31}$$

For the fourth dry year (2007):

$$\lambda_i = \frac{1.4281\ MAF}{0.074\ MAF + 16.119\ MAF} = \frac{1.4281\ MAF}{16.193\ MAF} = 0.088 \approx 0.09 \tag{32}$$

$$X_i = 16.119\ \text{MAF} * 0.09 = 1.4507\ \text{MAF} \tag{33}$$

Therefore, the allocation for the downstream agent for 2004 and 2005 are 1.2895 MAF while for years 2006 and 2007 are 1.4507 MAF.

3.6.2. Second Approach

3.6.2.1. For Upstream Agent

The main concept of the novel methodology that introduced by Mianabadi H. et al. (2014) was to divide the total deficit inversely proportional to agent's rate of contribution and rate of claims and subtract the loss of each agent (d_i) from the claim.

Total deficit (D) of the upstream agent is the difference between total system storage between the wet year and dry year. Considering the period from 1997 to 2017, the total system storage for the wet year and dry year are the same as above calculated values in table 2 and 3 respectively.

- Average total system storage (wet years) = 56.24 MAF

Total system storage (dry years) from 2004 to 2007 are respectively 35.8 MAF, 36.2 MAF, 35.0 MAF, and 37.4 MAF. Therefore, the total deficit for dry years can be obtained according to the following mathematical formula.

$$\text{Total deficit (D)} = \text{Average total system storage (wet years)} - \text{Average total system storage (dry years)} \tag{34}$$

Table 7

Total deficit (D) of the upstream agent

Year	Calculations	Total Deficit (MAF)
2004	56.24 – 35.8	20.44
2005	56.24 - 36.2	20.04
2006	56.24 – 35.0	21.24
2007	56.24 – 37.4	18.84

The deficit or the loss of agent (d_i) can be obtained using the rate of contribution, rate of claim, number of agents and total deficit. The total claim of the system for all four dry years can be obtained by adding the claim of upstream agent and downstream agent as the claim of the upstream and downstream agent are common for all dry years. The claim of the upstream agent is 56.1 MAF and claim of the downstream agent is 16.119 MAF. Therefore,

$$\text{Total claim } (C) = 56.1 \text{ MAF} + 16.119 \text{ MAF} = 72.219 \text{ MAF} \tag{35}$$

Same as the above calculation the total contribution can be obtained by adding the contribution of the downstream and upstream agent. But the total contribution for the dry years are different as the contribution of the downstream agent to the asset is slightly different for different dry years. Therefore, the total contribution for dry years can be shown as below table 6.

Table 8

Total contribution for dry years

Year	Upstream agent contribution (MAF)	Downstream agent contribution (MAF)	Total contribution (MAF)
2004	0.9230	1.3741	2.2971
2005	0.9230	1.3767	2.2997
2006	0.9230	1.3934	2.3164
2007	0.9230	1.4281	2.3511

Units: Million Acre Feet (MAF)

Using the rate of claim, and rate of contribution variables the d_i and X_i are calculated for dry years as follows:

- For the first dry year (2004):

$$d_i = \frac{\left(\frac{56.1\,MAF}{72.22\,MAF}+1-\frac{0.9230\,MAF}{2.2971\,MAF}\right)}{2} * 20.44\,MAF = 14.02 \text{ MAF} \tag{36}$$

The allocation of the upstream agent is:

$$X_i = 56.1 \text{ MAF} - 14.02 \text{ MAF} = 42.08 \text{ MAF};\ 0 \leq x_i \tag{37}$$

- For the second dry year (2005):

$$d_i = \frac{\left(\frac{56.1\,MAF}{72.22\,MAF}+1-\frac{0.9230\,MAF}{2.2997\,MAF}\right)}{2} * 20.04\,MAF = 13.78 \text{ MAF} \tag{38}$$

The allocation of the upstream agent is:

$$X_i = 56.1 \text{ MAF} - 13.78 \text{ MAF} = 42.32 \text{ MAF};\ 0 \leq x_i \tag{39}$$

- For the third dry year (2006):

$$di = \frac{(\frac{56.1\,MAF}{72.22\,MAF}+1-\frac{0.9230\,MAF}{2.3164\,MAF})}{2} * 21.24\,MAF = 14.64 \text{ MAF} \tag{40}$$

The allocation of the upstream agent is:

$$X_i = 56.1 \text{ MAF} - 13.78 \text{ MAF} = 41.46 \text{ MAF};\ 0 \leq x_i \tag{41}$$

- For the fourth dry year (2007):

$$d_i = \frac{(\frac{56.1\,MAF}{72.22\,MAF}+1-\frac{0.9230\,MAF}{2.3511\,MAF})}{2} * 18.84\,MAF = 13.04 \text{ MAF} \tag{42}$$

The allocation of the upstream agent is:

$$X_i = 56.1 \text{ MAF} - 13.04 \text{ MAF} = 43.06 \text{ MAF};\ 0 \leq x_i \tag{43}$$

The allocation of the upstream agent for the dry years 2004, 2005, 2006, and 2007 are 42.08 MAF, 42.32 MAF, 41.46 MAF, and 43.06 MAF respectively.

3.6.2.2. For Downstream Agent

Total deficit (D) of the downstream agent is the difference between the water release for the navigation at Gavin's point in the wet year and dry year. The average daily water release from Gavins Point for the wet years during the period of 1997 to 2017 is 33,212 cfs (16.119 MAF). Since this case study considers dry years, the average daily water release from Gavins Point for four dry years were calculated separately. The calculations can be shown as follows:

- For the first dry year (2004):

Total deficit (D) = Average daily water release (wet) - Average daily water release (dry)
= (16.14 – 10.90) MAF = 5.24 MAF (44)

d_i for the downstream agent can be calculated as follow:

$$d_i = \frac{(\frac{16.119\,MAF}{72.22\,MAF}+1-\frac{1.3741\,MAF}{2.2971\,MAF})}{2} * 5.24\,MAF = 1.6375 \text{ MAF} \tag{45}$$

The allocation of the downstream agent is:

$$X_i = 16.119 \text{ MAF} - 1.6375 \text{ MAF} = 14.4815 \text{ MAF};\ 0 \le x_i \quad (46)$$

- For the second dry year (2005):

Total deficit (D) = Average daily water release (wet) - Average daily water release (dry)
= (16.14 – 9.64) MAF = 6.5 MAF (47)

d_i for the downstream agent can be calculated as follow:

$$d_i = \frac{\left(\frac{16.119\ MAF}{72.22\ MAF} + 1 - \frac{1.3767\ MAF}{2.2997\ MAF}\right)}{2} * 6.5\ MAF = 2.0300 \text{ MAF} \quad (48)$$

The allocation of the downstream agent is:

$$X_i = 16.119 \text{ MAF} - 2.03 \text{ MAF} = 14.089 \text{ MAF};\ 0 \le x_i \quad (49)$$

- For the third dry year (2006):

Total deficit (D) = Average daily water release (wet) - Average daily water release (dry)
= (16.14 – 10.30) MAF = 5.84 MAF (50)

d_i for the downstream agent can be calculated as follow:

$$d_i = \frac{\left(\frac{16.119\ MAF}{72.22\ MAF} + 1 - \frac{1.3934\ MAF}{2.3164\ MAF}\right)}{2} * 5.84\ MAF = 1.8154 \text{ MAF} \quad (51)$$

The allocation of the downstream agent is:

$$X_i = 16.119 \text{ MAF} - 1.8154 \text{ MAF} = 14.3036 \text{ MAF};\ 0 \le x_i \quad (52)$$

- For the fourth dry year (2007):

Total deficit (D) = Average daily water release (wet) - Average daily water release (dry)
= (16.14 – 7.6173) MAF = 8.52 MAF (53)

d_i for the downstream agent can be calculated as follow:

$$d_i = \frac{\left(\frac{16.119\ MAF}{72.22\ MAF} + 1 - \frac{1.4281\ MAF}{2.3511\ MAF}\right)}{2} * 8.52\ MAF = 2.6233 \text{ MAF} \quad (54)$$

The allocation of the downstream agent is:

$$X_i = 16.119 \text{ MAF} - 2.6233 \text{ MAF} = 13.4957 \text{ MAF};\ 0 \le x_i \quad (55)$$

Therefore, the allocation of the downstream agent for the dry years 2004, 2005, 2006, and 2007 are 14.4815 MAF, 14.089 MAF, 14.3036 MAF, and 13.4957 MAF respectively.

3.6.3. Third Approach – The Proportional Rule

Since this approach provides a solution which is to allocate an equal share of the asset between the players, each agent in the system get an equal proportion. Calculations of this approach for four dry years are as follows:

- For the first dry year (2004):

$$\beta = \frac{2.2971\ MAF}{72.219\ MAF} = 0.0318 \approx 0.03 \tag{56}$$

- For the second dry year (2005):

$$\beta = \frac{2.2997\ MAF}{72.219\ MAF} = 0.0318 \approx 0.03 \tag{57}$$

- For the third dry year (2006):

$$\beta = \frac{2.3164\ MAF}{72.219\ MAF} = 0.0320 \approx 0.03 \tag{58}$$

- For the fourth dry year (2007):

$$\beta = \frac{2.3511\ MAF}{72.219\ MAF} = 0.0325 \approx 0.03 \tag{59}$$

3.6.3.1. For Upstream Agent

The allocation for the upstream agent would be different from the downstream agent as the equal proportion ratio is multiplied by each agent's claim. The allocation of the upstream agent is the same allocation for all four dry years as the above-calculated proportions are the same four dry years and the claim of the upstream agent is also constant for all years. Therefore, the allocation of the upstream agent is:

$$X_i^{PRO} = 0.03 * 56.1 \text{ MAF} = 1.683 \text{ MAF} \tag{60}$$

3.6.3.2. For Downstream Agent

The claim of the downstream agent is 16.119 MAF. Same as the upstream agent, the downstream agent's calculated proportions and the claim for all four dry years are constantly resulting in the same allocation for the four dry years. The allocation of the downstream agent can be shown as follows:

$$X_{\mathrm{i}}^{\mathrm{PRO}} = 0.03 * 16.119 \text{ MAF} = 0.4836 \text{ MAF} \tag{61}$$

3.6.4. Fourth Approach – CEA Rule

The concept of this approach is to allocate the lowest claim between all the players, and once the beneficiary with the lowest claim was fully satisfied, then that beneficiary will be excluded in the process. The same process will continue until the other creditors receive the unsatisfied claim from the remaining available water resource. Since this study only two agents were considered, the initial allocation will be the lowest claim of agents, and it will distribute among the other agent as well. In this case study, the upstream claim is 56.1 MAF, and the downstream claim is 16.119 MAF. According to the claims of the two agents, the lowest claim is 16.119 MAF. Therefore, this amount will be distributed among the two agents initially. After that allocation, if there is water available the unmet claim of the upstream agent which is 39.981 MAF will be allocated to the upstream agent.

Since in this study $E < C$ and there are only two agents this provides a unique solution. According to Madani et al., (2014) any step of this process including the initial allocation step if allocating the lowest claim among agents is not feasible due to the inefficiency of water availability, the available water will be distributed equally among the agents. As a result, this study will distribute the total available water equally among the downstream and upstream agent.

Table 9

Water allocation for four dry years

Year	E_U	E_D	Total water availability	Water allocation (X)
2004	0.9230	1.3741	2.2971	1.1486
2005	0.9230	1.3767	2.2997	1.1499
2006	0.9230	1.3934	2.3164	1.1582
2007	0.9230	1.4281	2.3511	1.1756

Units: Million Acre Feet (MAF)

3.6.5. Fifth Approach – Proposed Modified CEA Rule

The primary variable in this approach to allocate water is obtaining the percentage of the lowest claim. The percentages of claims can be calculated as below.

Considering the upstream agent's claim which is 56.1 MAF, the percentage of the claim is:

$$C_a = \frac{56.1}{72.22} * 100\% = 77.7\% \tag{62}$$

Considering the downstream agent's claim which is 16.119 MAF, the claim percentage is:

$$C_a = \frac{16.119}{72.22} * 100\% = 22.3\% \tag{63}$$

According to the results, the lowest claim percent is 22.3% which is downstream agent's claim. Initially, the lowest percentage of available water will be distributed among the two agents. Initial water allocation to both downstream and upstream agent is:

$$\text{Initial water allocation } (X_i) = 2.3161 \text{ MAF} * 22.3\% = 0.5165 \text{ MAF} \tag{64}$$

Since the downstream agent is fully satisfied, the next stage of this process is to distribute the remaining available water to the upstream agent. The remaining water after the initial allocation which is 1.2831 MAF (2.3161 MAF – (2*0.5165)) will be allocated to the upstream agent in the second stage process. The total water received to upstream agent after two process stages are 1.7996 MAF which is the same as demanded water by the upstream agent according to the proposed novel methodology. This can be shown in the mathematically:

$$\text{Demanded water by the upstream agent} = \text{total available water } (E_i) * 77.7\%$$
$$= 2.3161 \text{ MAF} * 77.7\% = 1.7996 \text{ MAF} \tag{65}$$

Therefore, both agents will be fully satisfied by this proposed novel methodology.

4. RESULTS AND DISCUSSION

This chapter illustrates the results of each bankruptcy allocation rules that have been used to address the water allocation issue in the Missouri River and discusses which method is most appropriate to this case study. Moreover, this chapter will compare the advantages and disadvantages of each bankruptcy allocation rules.

4.1. Results of Descriptive Analysis

Summary of Missouri River's agents' total available water, rate of contribution, claim, and claim of agents during dry years from the period 1997 to 2017 are shown in table 10.

Table 10

The average total available water, contribution rate, claim and claim rate on the Missouri River for dry years

	Upstream Agent	Downstream Agent
Total available water (E_i)	0.9230 (39.9%)	1.3931 (60.2%)
Contribution rate	0.3985 (39.9%)	0.6015 (60.2%)
Claim	56.1 (77.7%)	16.119 (22.3%)
Claim rate	0.7768 (77.7%)	0.2232 (22.3%)

Units: Million Acre Feet (MAF)

According to the results, the downstream agent has the highest average available water for dry years which is almost twice of the upstream agent's average value. The percentages of E_D and E_U are 60.2 and 39.9 respectively. Even though the upstream agent's total available water is less than the downstream agent, their claim is greater than downstream agent which is 77.7 percent while the downstream claim is 22.3 percent. The available water for upstream is the total system storage for the carryover multiple uses and this storage should maintain during the drought periods. Therefore, it is divided by multiple (Eight) years and then multiplied by the 47 days as this study is considering the dry years only. During dry years navigation channel is short of 47 days. Among all droughts that occurred in the United States, the "drought of record" happened during the 1930s and it was there for ten years. But in that period, there were some intermittent periods of partial recovery (https://drought.unl.edu/dustbowl/Home.aspx, accessed on 21st of March 2019). Hence, in this case study, the upstream agent has to maintain the multiple carryover use water storage for eight years. To calculate the total available water for the downstream agent, the river inflow from James and Big Sioux were considered assuming that James and Big Sioux rivers' water fluctuate same as the Missouri River.

The upstream agent claim is to manage their reservoir levels while the claim for the downstream agent is to manage the navigation channel during dry periods. The highest claim of the upstream agent implies that they demand water to maintain the reservoir level to carry out the multiple uses and also to release water from Gavins Point to the downstream to maintain the navigation channel.

4.2. Results of Different Allocation Rules

4.2.1. First Approach - SSR based PRO Rule

In this study, five main allocation rules were explored, and the first approach is SSR based PRO rule application. The results of this rule application can be shown as follows:

Table 11

Results of the first approach

	Upstream Agent				Downstream Agent			
	2004	2005	2006	2007	2004	2005	2006	2007
Available water (E_i)/ MAF	0.9230	0.9230	0.9230	0.9230	1.3741	1.3767	1.3934	1.4281
Claim (C_i)/ MAF	56.1	56.1	56.1	56.1	16.119	16.119	16.119	16.119
Allocation (X_i)/ MAF	0.6732	0.6732	0.6732	0.6732	1.2895	1.2895	1.4507	1.4507

Unit: Million Acre Feet (MAF)

Water availability of the upstream agent throughout all years are constant even for all approaches as they have to maintain the total system storage for multiple dry years while the water availability of the downstream agent is slightly different during dry years as the water flows from James, Big Sioux Rivers, and the Gavins Point is somewhat different in the years 2004, 2005, 2006, and 2007. The year 2007 has the highest available water allowing a few more days to maintain the navigation channel which is 205 days. Other years had only 198 days of navigation period. The claim of the upstream and downstream agent will be stay constant as they demand water to maintain the reservoir water level and navigation channel irrespective of the dryness of the year. The allocation of water in this approach is obtained by multiplying two variables which are allocation coefficient (λ) and agent's claim. The solution of this approach is to allocate 0.6732 MAF to the upstream agent for all four dry years. The reason is that the claim of the upstream agent and the calculated λ are constant for all years resulting in the same allocation solution to 2004, 2005, 2006, and 2007 dry years. On the other hand, the downstream agent's allocation is slightly heterogeneous across dry years due to the slight difference of the variables E_D and C_D. This approach suggests allocating water 1.2895 MAF and 1.4507 MAF in the years 2004, 2005 and 2006, 2007 respectively. Nevertheless, the allocation solution provided by this approach can be addressed by the total water availability to both upstream and downstream agent.

4.2.2. Second Approach

This approached was developed by Mianabadi et al. (2014) to address the shortcoming of the first approach as it favors the downstream agent over the upstream agent. The reason is that the upstream agent considers the claims of the downstream agent for the allocation, but the downstream agent does not consider the claims of the upstream agent for the allocation (Mianabadi et al., 2014). This study used this method to analyze how this approach provides a reasonable allocation solution to both agents.

Table 12

Results of the second approach

	Upstream agent				Downstream agent			
	2004	2005	2006	2007	2004	2005	2006	2007
Total deficit (D)	20.44	20.04	21.24	18.84	5.24	6.5	5.84	8.52
Loss for each agent (d_i)	14.02	13.78	14.64	13.04	1.64	2.03	1.82	2.62
Allocation (X_i)	42.08	42.32	41.46	43.06	14.48	14.09	14.30	13.50

Units: Million Acre Feet (MAF)

Results of the second approach provide allocation solutions to both downstream and upstream agent which are almost similar to each agents' claim. The allocation solutions obtained from this approach for the upstream agent are 42.08 MAF, 42.32 MAF, 41.46 MAF, and 43.06 MAF while for the downstream agent are 14.482 MAF, 14.089 MAF, 14.304 MAF, and 13.496 MAF for dry years 2004, 2005, 2006, and 2007 respectively. This approach provides allocation solutions according to the agents' contribution to the asset. Mianabadi et al. (2014) have stated that the agent with relatively large contributions to the asset and relatively low claims will get allocation solutions which are a relatively large proportion of their claim. The proportion of the upstream agent is 75.3% ((42.23/56.1) *100%) while the proportion of the downstream agent is 87.4% ((14.09/16.119) *100%). Results of this study also follow the concept as mentioned earlier where downstream agent contribute more to the asset and claim less resulting in the higher proportion of their claim.

4.2.3. Third Approach – PRO Rule

This approach provides all agents in the system equal proportion, but the water allocation to the agents will differ as the proportion is multiplied by the agents' claim where the claim of each agent is different from each other. Results of this approach in this study provide a similar proportion for four dry years which is 0.03. Therefore, the allocation to the upstream agent is 1.683 MAF and to the downstream agent is 0.4836 MAF for all dry years. This rule provides allocation solutions which can be distributed using the total available water to both agents. Since the equal proportions are distributed among agents, it might favor one agent more than others. Therefore, this rule does not provide a reasonable allocation solution to complex systems. But this rule provides a reasonable allocation solution to this study as this study considered only two agents.

4.2.4. Fourth Approach – CEA Rule

CEA rule favors the agents with the lowest claim as this approach distribute the lowest claim among agents initially and excludes that agent in the next stages in the process while the same process continues until remaining water resource is distributed. Since in this study the claim is much higher than the total available water, this approach provides a unique solution which is to distribute the total available water equally among upstream and downstream agents. Therefore, the allocation to the upstream and downstream agent for dry years 2004, 2005, 2006, and 2007 are 1.1486 MAF, 1.1499 MAF, 1.1582 MAF, and 1.1756 MAF respectively. The allocation solutions provided by this approach for this study are not accountable and acceptable as it only distributed water resources equally among agents. This rule will be appropriate for systems which have more than two agents, and the claim does not exceed the total available water.

4.2.5. Fifth Approach – Proposed Modified CEA Rule

This rule was proposed by this study to overcome the shortcoming of the CEA rule which can be applied to small systems such as two agent's system and when the claim exceeds the total available water.

Table 13

Results of the fifth approach

	Upstream agent	Downstream agent
Claim rate percentage	77.7	22.3
Initial water allocation	0.5165	0.5165
2nd stage water allocation	1.2831	-
Total water allocation	1.7961	0.5165

Units: Million Acre Feet (MAF)

The results of this proposed approach will satisfy both agents in the study as the procedure was able to allocate water according to their demanded claim rate percentages. The percentage of the total allocation to the upstream agent is 77.7% ((1.7961/2.3161) *100%) while the percentage of allocated water to the downstream agent is 22.3% ((0.5165/2.3161) *100%). Therefore, this proposed approach will be able to provide an allocation solution where both agents would accept the accountability of this approach.

4.3. Comparison between Bankruptcy Allocation Rules

To compare the results of allocation rules analyzed in this study overall values were used for all four dry years. The summary of the allocation rules can be shown as below table 14.

Table 14

Summary of analysis of allocation rules to the upstream and downstream agent

	SSR based PRO Rule	Mianabadi H. et al. Methodology	PRO Rule	CEA Rule	Proposed Rule
Upstream Agent	0.6732 (32.9%)	42.23 (75.0%)	1.683 (77.7%)	1.1581 (50%)	1.7961 (77.7%)
Downstream Agent	1.3701 (67.1%)	14.093 (25.0%)	0.484 (22.3%)	1.1581 (50%)	0.5165 (22.3%)

Units: Million Acre Feet (MAF)

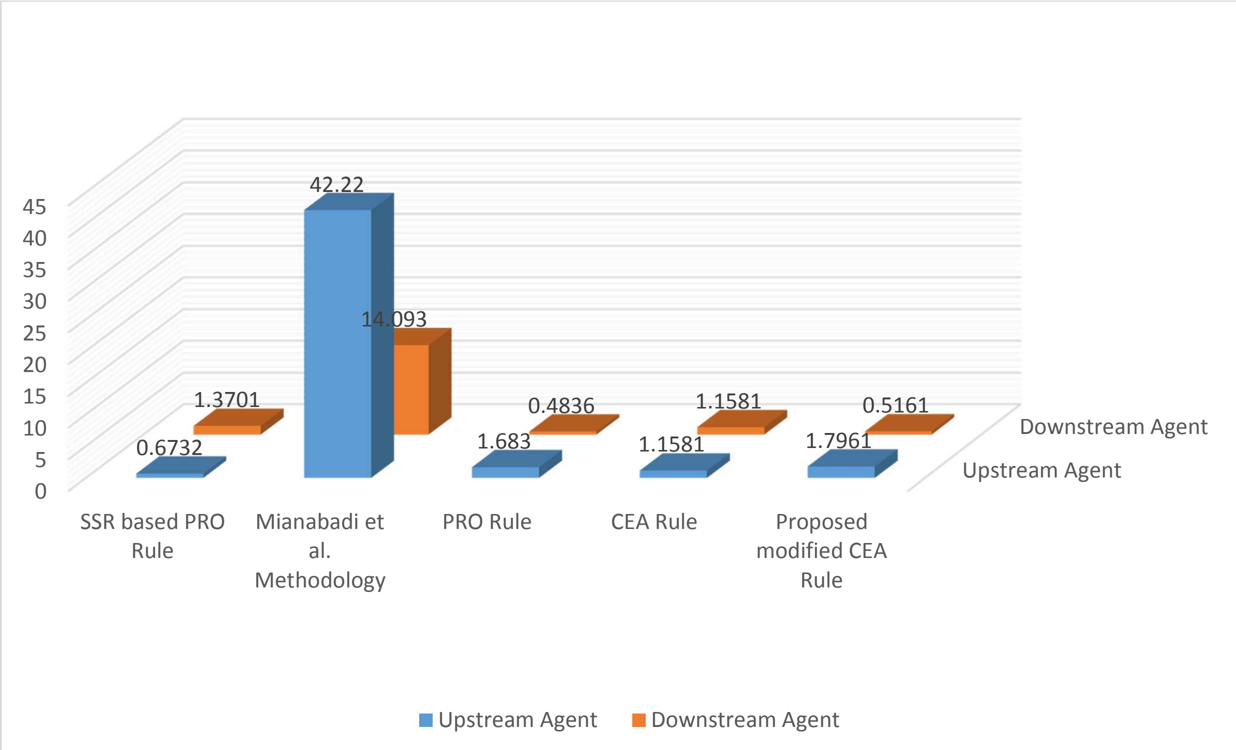


Figure 3. Distribution of different allocation rules to the agents. Units: Millions Acre Feet (MAF)

Based on the assumptions and fairness different allocation rules provide different allocation solutions. Madani and Lund in 2011 mentioned that the validity and acceptability of the allocation rules that used for a specific case study are always debatable as at least one beneficiary finds the solutions are unfair. The main reason is that in one allocation rule a beneficiary will gain more while in another allocation rule the same beneficiary will gain less.

According to the results obtained from the analysis of five bankruptcy allocation rules, none of the allocation rules exceed their claims. But the Mianabadi et al. (2014) allocation solutions exceed the total available water implicating that more resources are needed to meet the agent's demanded claim. Thus, this clearly does not resolve the bankruptcy problem. Out of five allocation rules, SSR based PRO rule and Mianabadi et al. (2014) approaches can be applied to river sharing issues where agents are linearly ordered. Since the agents of this study is linearly ordered and can identify as an upstream and downstream agent its applicability to this case study are unquestionable, but the solution provided by Mianabadi et al.'s methodology is questionable. Ansik and Weikard (2012) stated that the first approach favors the downstream agent as they receive large portion than the upstream agent which has been proved by this study as allocation solution provide 32.9% to the upstream agent while 67.1% to the downstream agent. Therefore, both approaches do not provide an allocation solution which meets fairness and unbiased to both upstream and downstream agent.

The other three allocation rules can be applied to any river sharing issues irrespective of its geographical order. According to Mianabadi et al. (2014), the application of PRO and CEA rules are questionable, and results of these rules may not consider because these rules do not consider the contribution of each agent to the total supply flow which leads no logical arguments. But since this study examines two agents and their claims exceed the total available water the accountability and fairness of the PRO, CEA, and proposed rules are unquestionable as they provide allocation solutions within the water availability range. Out of these three allocations rules the CEA rule favors the players with the lowest claim and if the claim exceeds the total water resources availability, its distributed equally among agents. Since this study's claim exceeds the total available water resources, the water resource is distributed equally among the upstream and downstream agents which will provide unfair allocation solution to one agent particularly the upstream agent as their claim is much larger than the downstream agent. Therefore, this approach to this study cannot be identified as an excellent approach to address the Missouri River sharing issue. On the other hand, this study proposed a modified CEA rule which will overcome the shortcomings of the CEA rule by considering the percentage of lowest claim to obtain the initial water allocation to the agents from the total available water and the results of this approach shows that the agents were fully satisfied along with their claim.

Comparing all allocation rules and assuming each agent select the highest allocation solution which satisfies their claim within the available water range, then the best approach will be the proposed modified CEA rule in this case study. The next preferred allocation solution will be the PRO rule as that also provide allocation solution within the total available water range.

5. CONCLUSIONS

Over the years, scholars have argued whether the solutions of non-cooperative or cooperative game theory are suitable for transboundary river sharing issues (Dinar et al., 1992; Mianabadi et al., 2015). According to Ambec and Ehlers (2008), some researches debated that the solutions of the non-cooperative game theory result in overutilization of the shared water resources. Recent scholars found that one of cooperative game theory tool, bankruptcy theory applies to resource sharing conflicts and this approach provide appropriate solutions to all beneficiaries when the claim exceeds the available resource (Mianabadi et al., 2015). As a result, this study used the bankruptcy allocation rules to address Missouri River conflicts and the results provided feasible solutions for the players. The allocation rules applied in this study was SSR based PRO rule, Mianabadi et al. (2014) methodology, PRO rule, and CEA rule. Apart from those rules this study developed and proposed a modified CEA rule to obtain allocation solution. The main features of this rule are to allocate resources within the water availability range and satisfy both agents in the system. The study explored two agents whose purpose of the water utilization were to manage the reservoir and to manage the navigation channel. Applying and comparing the allocation rules (SSR based PRO, Mianabadi et al.'s (2014), PRO, CEA, and Proposed modified CEA) the preferred approach to this case study is Mianabadi et al.'s (2014) methodology assuming the agents will select highest allocation solutions. But the results of this approach do not provide a solution within the water availability range. Therefore, considering the practical shortcoming of the Mianabadi et al.'s methodology, the best selection would be the proposed modified CEA rule to address the water allocation issue in the Missouri River. The significant difference between these two approaches is that Mianabadi et al.'s (2014) approach consider the contribution to the asset and the claims while the proposed methodology does not take in account the agent's contribution. Although the suggested method does not maximize the utilization considering the agent's contribution, this approach can be developed more to attain the economically feasible allocation solutions. The acknowledgment of the allocation solutions mainly depends on beneficiaries as one allocation rule will fair to one agent while it provides an unfair solution to another agent. Moreover, this study only explores the dry years as drought affects barge transportation significantly.

Since the maintenance of the navigation channel and reservoir level during dry years of the Missouri River can be identified more significantly important than other sectors such as hydroelectricity generation, irrigation, and municipal and industrial water supplies USACE can use the results of this study for allocation solutions. But this study does not explore all the allocation rules therefore concluding only the proposed modified CEA and PRO rule are the best approaches would be misleading.

Considering all the factors mentioned above, policymakers and researchers can use these approaches to address shared resources issues. Further studies on the application considering more players will provide more results. For instance, considering additional players such as irrigation, hydroelectricity generation, and municipal and industrial water supplies might address additional concerns from these sectors. As a branch of cooperative game theory, bankruptcy theory, can be used to assess the strategies for development of interstate river compacts. The results of the bankruptcy allocation rules can be used to address the competition between the states over water resource.

Moreover, to evaluate the bankruptcy allocation solutions whether beneficiaries will accept it, or not further studies on developing the Bankruptcy Allocation Stability Index (BASI) should be done. This will provide the stability and acceptability of the allocation solutions, which will support to select the best bankruptcy approach to address the water resources issues.

Considering the Missouri River case study even though other players such as irrigation, hydroelectricity generation can be identified in the system the bankruptcy model cannot use for a greater number of states as the contribution of navigation channel and reservoirs are significantly larger than other players. As a result, in this study the bankruptcy model can only use for upstream and downstream agents only. The findings of the bankruptcy models can be used to develop significant policy implications for water resource management.

REFERENCES

Abrams, R. H. (2002). "Interstate water allocation: A primer for eastern states." *U. Ark. L.R. Law Rev., 25*(1), 155-173.

Ambec, S., & Ehlers, L. (2008). Cooperation and equity in the river-sharing problem. In *Game theory and policy making in natural resources and the environment* (pp. 132-151). Routledge.

Ansink, E. J. H. (2009). *Game-theoretic models of water allocation in transboundary river basins*.

Ansink, E., & Weikard, H. P. (2012). Sequential sharing rules for river sharing problems. *Social Choice and Welfare, 38*(2), 187-210.

Aumann, R. J., & Maschler, M. (1985). Game theoretic analysis of a bankruptcy problem from the Talmud. *Journal of economic theory*, *36*(2), 195-213.

Becker, N., & Easter, K. W. (1997). Water diversion from the Great Lakes: is a cooperative approach possible? *International Journal of Water Resources Development, 13*(1), 53-66.

Bennett, L. L., Howe, C. W., & Shope, J. (2000). The interstate river compact as a water allocation mechanism: efficiency aspects. *American Journal of Agricultural Economics, 82*(4), 1006-1015.

Bureau of Reclamation History Program (2011). A Brief History Bureau of Reclamation. https://www.usbr.gov/history/2011NEWBRIEFHISTORY.pdf (accessed December 2018)

Chatain O. (2016) Cooperative and Non-cooperative Game Theory. In: Augier M., Teece D. (eds) The Palgrave Encyclopedia of Strategic Management. Palgrave Macmillan, London.

Dagan, N., & Volij, O. (1993). The bankruptcy problem: a cooperative bargaining approach. *Mathematical Social Sciences, 26*(3), 287-297.

Degefu, D. M., He, W., Yuan, L., & Zhao, J. H. (2016). Water allocation in transboundary river basins under water scarcity: a cooperative bargaining approach. *Water resources management*, *30*(12), 4451-4466.

Del Saz-Salazar, S., García-Rubio, M. A., González-Gómez, F., & Picazo-Tadeo, A. J. (2016). Managing water resources under conditions of scarcity: on consumers' willingness to pay for improving water supply infrastructure. *Water resources management*, *30*(5), 1723-1738.

Dellapenna, J. W. (2004). Special challenges to water markets in Riparian States. *Ga. St. UL Rev., 21*, 305.

Dellapenna, J. W. (2005a). "The Delaware and Susquehanna Basins." *Waters and water rights*, R. E. Beck, ed., Vol. 6, LexisNexis, New York, 251-275.

Dellapenna, J. W. (2005b). "Interstate struggles over rivers: The south-eastern states and the struggle over the 'Hooch.'" *NYU Envtl. Law J.*, 12(3), 828-900.

Dinar, A., Ratner, A., & Yaron, D. (1992). Evaluating cooperative game theory in water resources. *Theory and decision, 32*(1), 1-20.

Durant, R. F. (2011). Global crises, American public administration, and the "new interventionism" revisited. *Administration & Society*, *43*(3), 267-300.

Gächter, S., & Riedl, A. (2006). Dividing justly in bargaining problems with claims. *Social Choice and Welfare, 27*(3), 571-594.

Glennon, R. (2004). Water scarcity, marketing, and privatization. *Tex L. Rev., 83*, 1873.

Guhin, J. (1985). The law of the Missouri River. SD Law Rev, 30, 350-488.

Hearne, R. R. (2007). Evolving water management institutions in the Red River Basin. *Environmental Management, 40*(6), 842-852.

Hearne, R. R., & Prato, T. (2016). Institutional evolution of Missouri river management. *Water Policy*, *18*(3), 619-634.

Herrero, C., & Villar, A. (2001). The three musketeers: four classical solutions to bankruptcy problems. *Mathematical Social Sciences*, *42*(3), 307-328.

Hobbs, G. (2004). *Citizen's Guide to Colorado Water Law*, 2nd edn. Colorado Foundation for Water Education, Denver.

Hooper, B. P. (2011). Integrated water resources management and river basin governance. *Journal of Contemporary Water Research and Education, 126*(1), 3.

Houba, H., Do, P., Hang, K., & Zhu, X. (2014). Capacity choice of dams under rivalry use and externalities.

Hurwicz, L. (1973). The design of mechanisms for resource allocation. *The American Economic Review, 63*(2), 1-30.

Indiana Suggested Ordinance (2007). https://www.in.gov/dnr/water/files/Model_ordinance_Final_Draft_7-2-07.pdf (accessed April 2019)

Josephson, R. M. (1987). An analysis of the potential conflict between the prior appropriation and public trust doctrines in Montana water law. *Pub. Land L. Rev.*, 8, 81.

Madani, K. (2010). Game theory and water resources. Journal of Hydrology, 381(3-4), 225-238.

Madani, K., & Lund, J. R. (2011). A Monte-Carlo game theoretic approach for multi-criteria decision making under uncertainty. *Advances in water resources, 34*(5), 607-616.

Madani, K., Zarezadeh, M., & Morid, S. (2014). A new framework for resolving conflicts over transboundary rivers using bankruptcy methods. *Hydrology and Earth System Sciences, 18*(8), 3055-3068.

Mekonnen, M. M., & Hoekstra, A. Y. (2016). Four billion people facing severe water scarcity. *Science advances*, *2*(2), e1500323.

Mianabadi, H., Mostert, E., Pande, S., & van de Giesen, N. (2015). Weighted bankruptcy rules and transboundary water resources allocation. *Water Resources Management, 29*(7), 2303-2321.

Mianabadi, H., Mostert, E., Zarghami, M., & van de Giesen, N. (2014). A new bankruptcy method for conflict resolution in water resources allocation. *Journal of environmental management*, *144*, 152-159.

National Drought Mitigation Center (2019). The Dust Bowl. https://drought.unl.edu/dustbowl/home.aspx (accessed March 2019)

National Research Council. (2002). *The Missouri River ecosystem: exploring the prospects for recovery.* National Academies Press.

National Research Council. (2002). *The Missouri River ecosystem: exploring the prospects for recovery.* National Academies Press.

North, D. (1990). *Institutions, Institutional Change, and Economic Performance*. Cambridge University Press, Cambridge.

O'Neill, B. (1982). A problem of rights arbitration from the Talmud. *Mathematical Social Sciences*, *2*(4), 345-371.

O'Riordan, T. 1971. *Perspectives on Resource Management*. Pion: London.

Saleth, R. M., & Dinar, A. (2004). *The institutional economics of water: a cross-country analysis of institutions and performance.* The World Bank.

Schlager, E., & Heikkila, T. (2009). Resolving water conflicts: a comparative analysis of interstate river compacts. *Policy Studies Journal, 37*(3), 367-392

Schmeidler, D. (1969). The nucleolus of a characteristics function game. *J. Appl. Math*., 17, 1163-1170.

Sechi, G. M., & Zucca, R. (2015). Water resource allocation in critical scarcity conditions: a bankruptcy game approach. *Water resources management, 29*(2), 541-555.

Shapley, L. S., & Shubik, M. (1954). A method for evaluating the distribution of power in a committee system. *American political science review, 48*(3), 787-792.

Sherk, G. W. (2003). The management of interstate water conflicts in the twenty-first century: is it time to call uncle. *NYU Envtl. LJ, 12*, 764.

Tarlock, A. D. (2004). Water Law Reform in West Virginia, 106 W. Va. L. Rev, 495, 530.

US Army Corps of Engineers. (2006). Missouri River Mainstem Reservoir System: Master Water Control Manual Missouri River Basin.

Wolf, A. T. (1998). “Conflicts and cooperation along international water ways.” *Water Policy, 1*(2), 251-265.

Young, H.P. (1994). Handbook of game theory with economic application, Vol. 2. In: Aumann, R.J., Hart, S. (eds). Elsevier Science Publishers, pp. 1193-1235.

APPENDIX A. NAVIGATION SEASONS ON MISSOURI RIVER FROM 1980 TO 2017

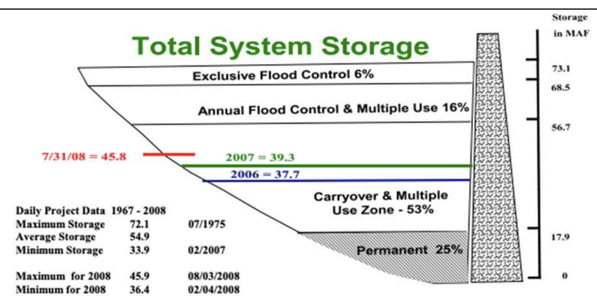
Year	Days of Navigation
1980	225
1981	222
1982 - 1987	245
1988	229
1989	205
1990 - 1992	205
1993	188
1994	245
1995	235
1996 - 1998	255
1999	237
2000 - 2001	245
2002	222
2003	239
2004 - 2006	198
2007	205
2008	215
2009 - 2015	245

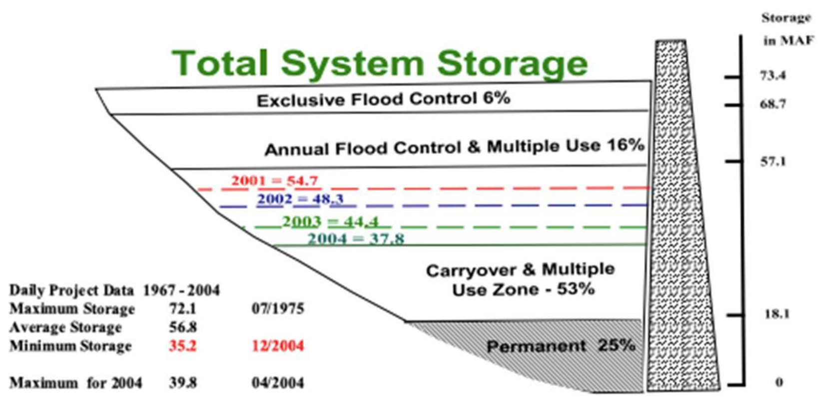
APPENDIX B. SUMMARY OF MISSOURI NAVIGATION PERIOD

Location	Start	End
Sioux City, Iowa	23^{rd} March	22^{nd} November
Omaha, Nebraska	25^{th} March	24^{th} November
Nebraska City, Nebraska	26^{th} March	25^{th} November
Kansas City, Missouri	28^{th} March	27^{th} November
Mouth near St. Louis, Missouri	1^{st} April	1^{st} December

The normal navigation season is eight months long.
Source: www.nwd-mr.usace.army.mil/rcc/tenmost/tenmosthll.html, accessed on 5th February 2019.

APPENDIX C. SUMMARY OF TOTAL SYSTEM STORAGE OF MISSOURI RIVER FROM 1997 TO 2017

Year	Month	System storage (MAF)	Description
2017	Nov 1	58.2	2.1 MAF above the base of the annual flood control and multiple use zone.
2016	Nov 1	57.2	1.1 MAF above the base of the annual flood control and multiple use zone.
2015	Nov 1	58.0	1.9 MAF above the base of the annual flood control and multiple use zone.
2014	August 31	61.3	5.2 MAF above the base of the annual flood control and multiple use zone.
	Nov 30	56.5	0.4 MAF above the base of the annual flood control and multiple use zone.
2013	August	53.0	3.1 MAF below the base of the annual flood control and multiple use zone, which had been adjusted from 56.8 MAF to 56.1 MAF
	Sep 1	52.1	4.0 MAF below the base of the annual flood control and multiple use zone.
2012	August 1	56.4	System storage has been decreased from Aug 1st to Nov 30th
	Nov 30	48.9	
	Sep 1	54.3	The September 1 System storage check of 54.3 MAF resulted in prescribed minimum winter releases of 12,000 cfs from Gavins during the 2012-2013 winter season.
2011			Long-term precipitation and temperature outlooks indicated that the fall and winter of 2011 would be wetter than normal.
2010	August 31	63.9	
	Sep 30	62.1	
	Oct 31	59.8	
	Nov 30	57.6	
2009	August 31	57.1	
	Sep 30	55.9	
	Oct 31	55.1	
	Nov 30	54.9	
2008	August 3	45.9	
2007	August 31	38.4	
	Sep 30	37.4	
	Oct 31	37.3	
	Nov 30	37.1	

Year	Month	System storage (MAF)	Description
2006	August 31	32.6	
	Sep 30	35.0	
	Oct 31	34.7	
	Nov 30	34.6	
2005	August 31	37.3	
	Sep 30	36.2	
	Oct 31	36.3	
	Nov 30	36.4	
2004	August 31	36.6	
	Sep 30	35.8	
	Oct 31	35.7	
	Nov 30	35.7	
	Dec 31	35.2	
2003	August 31	42.9	
	Sep 30	41.4	
	Oct 31	40.0	
	Nov 30	38.9	
2002	August 31	46.9	
	Sep 30	45.5	
	Oct 31	44.0	
	Nov 30	43.1	

Year	Month	System storage (MAF)	Description
2000 - 2001	Sep 1, 2000	54.4	
	Nov 1, 2000	51.0	
	July 31, 2001	54.6	
1999 - 2000	Sep 1, 1999	63.7	
	Nov 1, 1999	60.2	
1998 - 1999	Sep 1, 1998	61.8	
	Nov 1, 1998	60.2	
1997 - 1998	Sep 1, 1997	69.1	
	Nov 1, 1997	62.9	