ABSTRACT

Hydro-economic models (HEMs) are powerful tools to analyze water scarcity, drought, and water management problems. Though several HEMs reviews have been conducted in the recent past, none of them focused on the management of transboundary river water disputes, benefit sharing, or trade-offs. Therefore, this review explored how HEMs can suggest mitigating water sharing disputes on transboundary rivers. Though more than 300 HEMs have been developed worldwide, very few focused on transboundary river water disputes. After vigorous screening at Google Scholar, only 25 articles were found which focused on transboundary river water disputes. Most HEMs that were reviewed proposed to share benefits such as sharing hydropower produced from the river, reallocating water from low-value agriculture to high-value agriculture or managed operation of the dam, or other monetary compensation. But no study assessed non-water sector benefit sharing such as trade or transit. Most HEMs focused on irrigation and hydropower which are benefits from the river and very few studies focused on fisheries, environment, and wetland which are benefits to the river. International rivers can act as a catalyst among the riparian countries and promote cooperation in trade, commerce, exchange of technologies, and other fields. HEMs can play an important role in this regard. It is to be mentioned that HEMs cannot resolve water conflicts in a shared basin, they only can propose for the options of solution.

Key words: Benefit sharing, Hydro-economic model, Resolution of water dispute, Trade, Transboundary water dispute, Transit

HIGHLIGHTS

- How HEMs can suggest mitigating water sharing disputes on transboundary rivers.
- Only 25 articles focused on transboundary river water disputes.
- No study assessed non-water sector benefit sharing such as trade or transit.
- International rivers can act as a catalyst among the riparian countries and promote trade, commerce, exchange of technologies, and other fields.
- HEMs can play an important role in this regard.

INTRODUCTION

Sometimes, economic analysis can give better solutions to river management and identify efficient water allocations (Heinz et al., 2007; Harou et al., 2009). Hydro-economic models (HEMs) are powerful tools to analyze water scarcity, drought, and climate change issues. HEMs can be used to test the effects of infrastructural and policy responses developed to cope with water management problems (Kahil et al., 2015). Such models integrate hydrologic, economic, institutional, and environmental variables and involve some or all of the main
stakeholders in a basin, including farmers, hydropower producers, urban inhabitants, tourists, boatmen, fishermen, and aquatic ecosystems (Habteyes et al., 2015). The main purpose of HEMs is to identify opportunities to increase/maximize the total benefits in a basin, while some models explore the potential for the trade-off between different uses. HEMs can propose options to solve the management of transboundary river water disputes by benefit sharing. In other words, a social/political problem like water disputes may be solved through HEMs. The outcome of HEMs can help diplomats/politicians of co-riparian countries to understand water-sharing arrangements and negotiate with neighboring countries.

Different types of HEMs have been developed in different river basins depending on the catchment type, precipitation, demand, and policy context (Momblanch et al., 2016; Bekchanov et al., 2017). Examples include the Nile Economic Optimization Model (NEOM) for the Nile Basin, the Ganges Economic Optimization Model (GEOM) for the Ganges basin, and the Colorado River CALVIN model for the Colorado River (Wu et al., 2013; Digna et al., 2017). The first HEM on the Nile was developed by Whittington et al. (2005) to determine the pattern of water use that would give maximum benefits from agriculture and hydropower. Other researchers have extended HEM application to municipal and industrial use. Different models have analyzed the economic effects for different combinations of hydraulic structures and stakeholders (Strzepek et al., 2008; Basheer & Elagib, 2018; Basheer et al., 2018). An HEM for the Ganges, GEOM, maximizes benefits from multiple water uses. Besides hydropower and irrigation, the GEOM assessed the economic value for reduced flood losses and additional flow during the dry season (Wu et al., 2013). The CALVIN model was developed to allocate water to urban and agricultural use based on cost and benefits (Jenkins, 2001). This model was further developed and used by many researchers (Medellín-Azuara et al., 2007b, 2008).

HEMs economic structure can be categorized as computable general equilibrium (CGE) models and non-computable general equilibrium (non-CGE) models. Most CGE HEMs consider direct and indirect benefits, whereas non-CGE models consider only direct effects. Based on the solution methods, HEMs can be simulation and optimization or both simulation and optimization models (Bekchanov et al., 2015a). Simulation involves examining and evaluating specific situations under particular conditions (such as water demands or water treaty arrangements), while optimization models help identify ‘what’s best’ among many options (Heinz et al., 2007). Most of the HEMs are written in General Algebraic Modelling Systems (GAMS) language, whereas very few HEMs are written using River-Ware, HEC-HMS, and Crop Wat (Basheer et al., 2018).

An HEM has three components: (1) hydrology (water balance), (2) economics, including the calculation of benefits from water use, and (3) an objective function that introduces institutional rules/constraints that impact the hydrologic and economic components. Each of them is discussed below.

**Hydrologic Component:** Hydrology or water balance model provides information about the water availability in a region, river, lake, or other water body (Karimi et al., 2013; Kirby et al., 2015). Water balance may be calculated yearly, seasonal, monthly (Jalilov et al., 2015; Satti et al., 2015), fortnightly, weekly, daily, or even hourly depending on the purpose of the model, available data, and type of water body. The basic water balance for any region, water body, or river reach is described as total water in equal to total water out plus change of storage (Mainuddin et al., 2007).

**Economic Component:** The economic component of an HEM is the economic value of water from different water uses under different climatic, environmental, management, and economic conditions (Mainuddin et al., 2007). The economic values from different water uses in existing HEMs include but are not limited to agriculture, hydropower, industry, household, fisheries, navigation, tourism, and environmental.

**An objective function:** There are some water-sharing treaties or institutional rules on some rivers. Therefore, those sets of rules/constraints have to be followed during the preparation of HEMs on those rivers. For an instance, all the HEMs on the Nile introduce rules reflecting the water-sharing treaty between Sudan and Egypt (Whittington et al., 2005).
Scope of the review

Several hydro-economic modeling research reviews have been conducted in the recent past including Bekchanov et al. (2017), Momblanch et al. (2016), and Harou et al. (2009). The focuses and conclusions from these reviews emphasized somewhat different issues than those that are treated in this review.

The review by Heinz et al. (2007) focused on HEMs on European Water Framework Directives. On the other hand, the review articles by Brouwer & Hofkes (2008) described the key issues addressed by HEMs, limitations, and future research directions. The review article by Harou et al. (2009) of 60 HEMs described the valuation methods of water followed by the model developers for different uses including urban, agriculture, hydropower, environment, and recreation. The review also identified the key steps in model design, solution techniques, spatial and temporal scales. They grouped HEMs according to the following categories of application: (1) Instream and offstream or intersectoral allocation (13 papers), (2) Water supply engineering infrastructure and capacity expansion (10 papers), (3) Conjunctive use of groundwater and surface water (18 papers), (4) Institutions, water markets, and pricing (14 papers), (5) Conflict resolution, transboundary management, and sustainability (7 papers), (6) Managing for climate change and drought (5 papers), and (7) land use management: flood and water quality (3 papers). They also discussed current limitations of the approach, suggested directions for future work, and recommended ways to improve policy relevance.

Harou et al. (2009) concluded that there is a gap between HEMs’ output and their application. To mitigate the gap, more collaborative conflict resolution approaches should be introduced, with HEMs widely applied by academics put to more use in policy circles. It is noted that, to date, they mostly have not been accepted warmly by policymakers, water managers, operators, and practitioners. They predicted more use of HEMs in the future to evaluate water scarcity, re-allocation, re-operations, water-use efficiency, water quality, and environmental water value trade-offs.

Momblanch et al. (2016) selected 95 articles with an emphasis on environmental issues evaluated with HEMs including flows, water quality, recreation, flood control, and vegetation. The article identified that the representation of environmental values of water is absent in most applications, and there is scope to include environmental values. The review discussed the valuation methods that can be applied to environmental water and made recommendations on how to improve environmental valuation in HEMs. The study also assessed whether the environment was considered as a constraint or valued in economic terms in the HEMs reviewed. The review revealed that livestock, tourism, navigation, and industrial water values are rarely included in HEMs. Moreover, many issues such as drought or climate change management, transboundary water management, conjunctive use of surface–groundwater are less commonly treated in the HEMs reviewed. The study found no systematic approach to the valuation of ecosystem services in HEMs related to regulating and cultural ecosystem services. The review concluded that a more holistic representation of the environment in HEMs is required.

Bekchanov et al. (2017) considered 97 peer-reviewed studies. He discovered recent advances in HEMs focusing on different applications of HEMs, systematic comparison of HEMs including main themes studied, scenarios, indicators, sectors, functional relationships, and region/areas/rivers where HEM studies have been carried out. Moreover, different model structures and the distinction between different model types were noted. The review expressed deep concern about the challenges of HEM which includes but not limited to data, representation of results, and involving stakeholders and policymakers. The review advised that future research should focus on water, energy food nexus, include non-market ecosystem services and water quality aspects, and calculate the effect of water allocation. The study concluded that sound analysis of water–energy–food production, further inclusion of water management and environmental impact of water use, improvement
of the model, and making model result more interpretable, will make HEMs more popular among water managers.

There has been no review of HEMs to date with a primary focus on the management of transboundary river water disputes, benefit sharing, or trade-off. Though there is some reference to related issues in several of the reviews discussed above, those studies did not explore the strategies of dispute resolution. This review has addressed this gap by providing an overview of how HEMs have been used in the published journal literature to analyze transboundary water trade-offs and evaluate options for the resolution of the water dispute.

Objectives of the review

The review aims to look at how HEMs can suggest mitigating water sharing disputes among co-riparian countries on transboundary rivers. Our specific objectives are

- Review studies that applied HEMs to transboundary rivers and addressed water allocation issues.
- Discuss the model features, limitations, including how water networks are represented, how models are calibrated, which economic sectors are represented, and how economic values are estimated.
- Estimate the scale of economic benefits from Transboundary Water Agreement (TBW) or benefits of cooperation among riparian countries.
- Define what transfers of water between countries and sectors would be required to achieve the most benefits from the river basin.
- Describe which sectors/countries would have to compensate other sectors/countries so that no country or sector is left worse off.

METHODS

We searched the literature on the Google Scholar database. Then, the research was extended to other research basis such as Elsevier, Taylor and Francis, Springer, Willey, Emerald, and Oxford University Press. At first, articles were searched with keywords including transboundary water dispute, HEM, resolution of water dispute, benefit sharing, and more than 300 papers were found. But these papers focused on a variety of water-related issues such as water quality, the effect of drought or climate change, water purification, desalination, and so on. Then the set of relevant articles was narrowed by excluding articles that did not analyze some form of transboundary water dispute, benefit sharing, or trade-off. This process reduced the number of relevant articles to 80. Next, we read the title, abstract, introduction, conclusion to narrow to a set of 75 articles that were peer-reviewed and provided sufficient information about a water dispute, conflict, or management approach to evaluate for this review. The methodology is presented in Figure 1.

Many studies were about transboundary rivers but focused only on a specific country or part of the river such as Mullick et al. (2014) focused only on Bangladesh, Yang et al. (2014) and Hashmi et al. (2019) focused only on Pakistan and therefore were rejected. Some studies evaluated transboundary water quality or climate change impacts (Kandulu & Connor, 2017) which was not our focus and thus these were excluded (Amjath-Babu et al., 2019; Burek et al., 2019; Kahil et al., 2019; Kaysay et al., 2019; Paulos, 2019; Teotónio et al., 2020). On the other hand, five papers were rejected as they were not peer-reviewed (Siehlow et al., 2012; Oei & Siehlow, 2014; Siddig et al., 2019; Abdulloev, 2020). The review revealed that some authors published many similar articles on the same river basin. So, one was selected from them and others were not included (e.g. Cai & McKinney, 1997, 1999).

Our main focus was on benefits maximization, benefit sharing, trade-off, transnational conflict resolution, and the most related 25 articles were selected after vigorous screening. The papers reviewed are listed in Table 1.
Because the set of transnational HEMs involving transboundary water that we filtered down to was small, we also selected nine representative HEMs where interstate water sharing dispute is severe such as Australia, India, and China. We selected some representative studies from each country or area including four from Australia, two from Spain, one from India, one from Pakistan, and one from China. Finally, we include some HEM studies related to cities states level transboundary water issues. This included studies from Baja California, Mexico, and Central California, the USA where there are disputes among different user groups such as farmers, domestic users, hydro-power users, and environmental use. We selected six HEMs of this type (three from the USA and three from Mexico). More detail on articles and major findings is presented in Supplementary material, Appendix A.

Summary of the review
The major findings of the review are described in the following sections.

Benefit sharing
Various methods are followed to resolve water disputes. The first step is dialogue or negotiation. There is no fixed method to initiate negotiation rather it depends on the geography, socio-economy, culture, religion, and historical relationship of that riparian countries (Petersen-Perlman & Wolf, 2015). The other dispute resolution methods are mediation by a third party, benefit sharing diplomacy, international court of justice, and using military power (Browder, 2000; Nandalal & Simonovic, 2002). According to a study by Hossen et al. (2021), benefit
| Name of river basin | Suggestion to resolve water dispute | Types of benefit sharing | References |
|--------------------|------------------------------------|--------------------------|-----------|
| The Nile           | Suggested for intercountry and intersector trade-off | Benefits to the river, Benefits from the river | Whittington et al. (2005) |
|                    | No suggestion                       | Benefits from the river   | Strzepek et al. (2008)  |
| The Blue Nile      | Trade-off between hydropower and irrigation in Sudan is possible | Benefits from the river | Satti et al. (2015) |
|                    | Managed operation of the dams       | Benefits from the river   | Habteyes et al. (2015)  |
|                    | There is a provision of power trade from Ethiopia to Sudan. Managed operation of the dams | Benefits from the river | Jeuland et al. (2017) |
|                    | Cooperation between Ethiopia and Sudan can maximize benefits | Benefits from the river   | Basheer et al. (2018)   |
| The Mekong         | Improve irrigation efficiency and cooperation. Trade-offs between instream and offstream, upstream and downstream water uses are possible | Benefits to the river, Benefits from the river | Ringler et al. (2009) |
|                    | Trade-off between various sectors is possible | Benefits to the river, Benefits from the river | Ringler & Cai (2006) |
|                    | Cross-sectoral and transboundary stakeholders should participate in operating reservoir | Benefits from the river   | Do et al. (2020)         |
| The Amu Darya      | Trade-off between upstream hydropower and downstream agriculture. Water can be stored in upstream during the winter and released during summer for downstream irrigation. Downstream states can supply energy resources (natural gas, oil, coal) during winter | Benefits to the river, Benefits from the river Beyond the river | Jalilov et al. (2015), Jalilov et al. (2016), Jalilov et al. (2018) |
|                    | There is potential for a trade-off between upstream hydropower and downstream agriculture. The Rogun dam can be operated cooperatively | Benefits to the river, Benefits from the river | Bekchanov et al. (2015b) |
|                    | Managing water Structures with cooperation. Trade hydroelectricity to downstream countries | Benefits from the river   | Bhaduri & Bekchanov (2017) |
| The Zambezi River  | Zambia and Mozambique will have to compensate Angola and Namibia to achieve maximum benefits | Benefits from the river   | Tilmant & Kinzelbach (2012) |
| Volta River (West Africa) | There is potential to increase economic benefits to Ghana and Burkina Faso, with no economic loss to any other riparian, from the development storage structure | Benefits from the river   | Baah-Kumi & Ward (2020) |
| The Brahmaputra River | No suggestion                       | Benefits from the river   | Yang et al. (2016)       |

(Continued.)
Sharing is the most efficient method to resolve transboundary water disputes. Sadoff & Grey (2002) refer to sharing four types of benefits: benefits to the river, benefits from the river, benefits due to the river, and benefits beyond the river. Though various types of benefits sharing process, most HEMs that were reviewed focused on irrigation and hydropower which are benefits from the river, and very few studies focused on fisheries, environment, wetland which are benefits to the river.

### Study area of the HEMs

There are many HEMs for the Nile River that evaluate the river basin’s water sharing disputes. There are many studies on the Murray-Darling River basin that relate to water sharing. HEMs are also relatively well developed on rivers between the USA and Canada. There are a significant number of HEMs on Amu and Syr Darya evaluating transboundary water disputes. One possibility might be the presence of a formal river basin compact.

**Table 1.** | Continued

| Name of river basin | Suggestion to resolve water dispute | Types of benefit sharing | References |
|---------------------|-------------------------------------|--------------------------|------------|
| The Ganges          | Modernization of irrigation system. There is a potential trade-off between irrigation water usage in India and low-flow augmentation in Bangladesh | Benefits from the river | Wu et al. (2013) |
| Karnali-Mohana and Mahakali (tributary of Ganges) | Trade-offs both within and across sectors. There are substantial trade-offs between irrigation in Nepal and water use in India | Benefits from the river | Pakhtigian et al. (2019) |
| The Euphrates River | Downstream country can compensate the upstream to release more water with a rate of $0.089/m³. Turkey needs to be compensated by money (Turkey’s $1 benefits cause $4.2 loss for downstream countries) | Benefits from the river | Aytemiz (2001) |
| Amu-Syr Darya       | Cooperation and Inter-catchment water rights trading can increase basin-wide benefits | Benefits to the river, Benefits from the river | Bekchanov et al. (2015a) |
|                     | Monetary compensation to farmers, Inter-subcatchment trade-off, improve irrigation efficiency | Benefits to the river, Benefits from the river | Bekchanov et al. (2018) |
| The Syr Darya       | Improvements in the current infrastructure, increase irrigation efficiency and changes in current crop patterns are necessary | Benefits to the river, Benefits from the river | Cai et al. (2002) |
|                     | Managed operation of the reservoir. Store water in winter to release in summer | Benefits to the river, Benefits from the river | Cai et al. (2003) |
|                     | International cooperation in the power sector may reduce upstream–downstream conflicts | Benefits beyond the river | Luchner et al. (2019) |
|                     | The upstream country (Kyrgyzstan) can be encouraged through compensatory payments. Downstream countries may supply fuel to upstream countries to for summer irrigation releases from the Toktogul reservoir | Benefits from the river, Benefits beyond the river | Teasley & McKinney (2011) |
commission to monitor and measure water withdrawals and to encourage economic analysis of the withdrawals’ value. On the other hand, there are very few HEM studies relevant to transboundary water disputes on the Mekong, Ganges, Indus, and Brahmaputra. Probably, there are not enough economists in this region who can develop HEM. Figure 2 shows the area where HEMs have been applied.

Outcomes/main theme of the HEMs

The purpose of most HEM studies was to increase/maximize the total benefits in the basin. Though the HEM results demonstrate opportunities for improved efficiency, many studies (cites) describe that many disputes are focused on other than efficiency issues such as perceived inequity (Tilmant & Kinzelbach, 2012), transactions costs (Satti et al., 2015; Bhaduri & Bekchanov, 2017; Jeuland et al., 2017), and opportunity cost involved for one party in the dispute (Teasley & McKinney, 2011; Kucukmehmetoglu, 2012).

Some studies estimated economic benefits if the river water can be used in a fully cooperative fashion.

A study on the Zambezi estimated that the yearly average cost of non-cooperation for the river basin is 350 million USD, which is 10% of the total annual water benefit estimated to result from current less cooperative basin management (Tilmant & Kinzelbach, 2012). The HEM studies on the Nile estimated potential annual economic benefits from cooperative water management of USD 7–11 billion (Whittington et al., 2005), and the total annual gain possible from improved management of the High Aswan Dam (HAD) is estimated at 7.1 billion to 10.3 billion EGP (Strzepek et al., 2008) for a scenario that redistributes water and provides compensation without making any country worse off. A study on the Nile by Whittington et al. (2005), similarly suggests that if full cooperation on a set of proposed hydropower and wetland project were completed, potential annual economic benefits would be USD 4.9 billion (Ethiopia USD 3. billion, Egypt, USD 1.1 billion, others USD 1.1 billion) without making any country except Sudan worse off (Sudan is estimated to lose USD 210 million). Another study by Habteyes et al. (2015) shows that Ethiopia can be better off (Ethiopia can gain a total of 2.6 billion), and no country would be worse off from a better-managed operation of Ethiopian and Egyptian dams. Another study shows that Ethiopia’s economic benefits can be increased 5–6 times without significant harm to downstream countries if Grand Ethiopian Resonance Dam (GERD) can be operated with full cooperation (Jeuland et al., 2017). Another study on the Amu Daria River by Jalilov et al. (2015) shows that potential optimal benefits (USD 45,887) are much higher than baseline benefits (USD 31,110). He suggested that the energy benefits

![Fig. 2. Name of the river basins that were addressed by the models.](http://iwaponline.com/wp/article-pdf/doi/10.2166/wp.2021.114/948682/wp2021114.pdf)
gained by Tajikistan could lead the country to provide some support for the downstream countries to reschedule their agricultural pattern to adjust with the changed water flows.

Many studies explored the potential for trade-off. Seven papers found potential for trade-off between upstream hydropower vs downstream irrigation as hydropower is typically more profitable than irrigation. Four articles found potential trade-offs between instream and offstream water uses. Instream use refers to water use taking place within a stream such as hydroelectric power generation, navigation, fishing, and recreational activities, whereas offstream use refers to water diverted from a groundwater or surface water source for public water supply, industry, irrigation, livestock, thermoelectric power generation, or other uses. A study on Sudanese Blue Nile shows trade-offs between hydropower (instream) and irrigation (offstream use) (Satti et al., 2015). Another study by Ringler et al. (2004) describes that offstream uses (such as municipal) are more beneficial than instream use (such as fisheries or navigation).

Inter-subcatchment trade-off analysis has also featured in some studies (Ringler & Cai, 2006; Mainuddin et al., 2007; Kahil et al., 2015), which shows that when some crops and regions produce more irrigation value per unit water than others, inter-subcatchment water re-allocation can increase the total value of water use.

The HEMs reviewed used different types of assessment criteria to design and test water management solutions. Most of the papers used a net benefit maximization approach, whereas some papers emphasized specific sector priorities like upstream hydropower or downstream agriculture (Jalilov et al., 2015). Some studies followed specific water treaty/water sharing rules and therefore were constrained to allocate/release water to some sectors. For instance, the constraints used in the NEOM include storage capacity constraints, irrigation water withdrawal constraints, hydropower generation capacity constraints, and non-negative constraints (Whittington et al., 2005).

It was observed that 19 out of 25 of the reviewed HEMs were optimization models, two were simulation, and the remainder were both optimization and simulation.

Hydrological network
All the HEMs presented the river basin framework as a node-link network, a representation of the spatial objects in the river basin. Nodes represent river flows, reservoirs, or diversion points, and links represent the linkages between these objects. All the models considered agricultural diversion, hydropower dam, evaporation, reservoir release, and streamflow data at the inflow. Some models considered evaporation, seepage with high importance (such as the NEOM), some models considered domestic/industrial water use, some considered return flow while some considered glacier melt, rainfall-runoff, and groundwater pumping data. The reasons for not considering some parameters are the negligible amount of non-availability of reliable data. Water network for two models are simple (Mainuddin et al., 2007; Strzepek et al., 2008; Satti et al., 2015), six HEMs are complex such as Basheer et al. (2018) and Jalilov et al. (2015), and nine models are very complex such as Whittington et al. (2005) and Ringler et al. (2004). Figure 3 shows the number of papers that used different parameters in their models.

Economic uses/sectors
Different models considered different numbers of economic sectors ranging from 1 to 6 as shown in Figure 4. Out of 40 papers that have been reviewed, 21 papers addressed two sectors (13 papers agriculture and hydropower, 5 papers agriculture and environment, 2 papers agriculture and domestic, 1 paper recreation and hydropower), 8 papers considered three sectors, 5 papers considered four sectors, 3 papers considered five sectors, 2 papers considered six sectors, while 1 paper considered only one sector (agriculture).

All the models considered the economic use of agriculture and many models considered hydropower use. On the other hand, 18 models considered industry and household, whereas few studies considered fisheries and navigation (Strzepek et al., 2008; Ringler et al., 2009) and very few models considered tourism (Strzepek et al., 2008).
Sixteen papers (Mainuddin et al., 2007; Ringler et al., 2009; Kahil et al., 2015) considered environmental benefits or wetlands. The potential benefits from proposed hydropower had been taken into consideration by most of the models. Livestock, industrial use were not considered as separate use in any of the studies reviewed. Figure 5 shows various economic sectors that were considered by the models.

**Calibration and validation**

Many of the models reviewed were calibrated to fit model predictions suitably close to observed historical values of flow, hydro production, crop production, cropland pattern in each basin country in the baseline scenario. For example, the model by Mainuddin et al. (2007) was calibrated for annual flows from July 2000 to June 2001 and validated for a dry (1994–1995), normal (1995–1996), and a wet year (1996–1997). Most models (Ringler & Cai, 2006; Strzepek et al., 2008; Ringler et al., 2009) were calibrated with a specific year data which were not a too dry or wet year, whereas some models were calibrated with average data. Many models (Strzepek et al., 2008) were
validated for a long time depending on the data availability. Some models were run for 20 years or longer time series for calibration generally produce more certainty. In contrast, some studies did not mention how they were calibrated or validated (Whittington et al., 2005; Bekchanov et al., 2015a; Jeuland et al., 2017). Most of the models were formulated for 1 year and run with a monthly time step. Some models considered three cropping seasons, whereas some models considered two cropping seasons (Jalilov et al., 2015).

Uncertainty analysis
Usually, any uncertainty analysis aims to forecast scenarios of increased costs and decreased benefits that may arise. It can estimate the probable effects of one or more variables. Among the articles reviewed, 10 studies considered river flow, and 4 papers considered climate change uncertainty and consequently considered flow as uncertain parameters (such as Satti et al. (2015), Whittington et al. (2005), Habteyes et al. (2015), and Jeuland et al. (2017)). Climate change sensitivity scenarios of higher flow (+20%) and lower flow (−20%) than base case level in the Blue Nile represent one of the only HEMs on transboundary issues we reviewed that considered this factor (Satti et al., 2015). Several of the reviewed HEMs considered hydropower price uncertainty (Jeuland et al., 2017; Pakhtigian et al., 2019). The current price and half this amount 8 to 4 cents kW/h were considered by Satti et al. (2015). Other studies considered irrigation area as an uncertain parameter since irrigation area changes every year. Besides, some of the studies reviewed carried out uncertainty analysis on water price as irrigation water price depends on demand and supply such as Whittington et al. (2005). Moreover, crop price was considered as a uncertain parameter by some of the evaluated studies (Bekchanov et al., 2018).

Dispute resolution
Figure 6 shows the different approaches to mitigating disputes modeled in the studies that were reviewed. Most of the studies modeled some type of cooperation, trust, and coordinated management in the operation of the dams/hydraulic structures. Many others evaluated improved water structures or management to increase irrigation efficiency. The focus of most of the studies was on quantifying possibilities to reduce intercountry, intersector, or inter-subcatchment trade-offs, by reallocating water among uses and locations and compensating for the loss in net gain scenarios. For example, many studies evaluated the trade-offs between upstream hydropower vs downstream agriculture to understand the possibilities to increase total benefit and who would lose (require
compensation) and who would gain in such scenarios. Some authors suggested compensation mechanisms such as exporting power to countries that lose hydropower.

Limitations
All of the models reviewed have limitations, many relating to lack of data. For example, neither sediment transport nor groundwater flows were incorporated explicitly in the NEOM model. Moreover, this is an annual model and does not address the complexity of over-year storage problems. The effect of flooding was not addressed by any model.

All the models have numerous assumptions in calculating benefits. Most of the models did not consider the cost of future hydropower installation, operation, and maintenance costs. The NEOM assumed the same irrigation price for all the riparian countries and considered constant demand for water in agriculture and hydropower.

Research/knowledge gap
Some economic values like benefits due to flood control by dams, environmental benefits due to flow have not been quantified in HEMs addressing transboundary water disputes and sharing. The models reviewed also failed to quantify economic cost due to dams or barrages such as environmental degradation, loss of flora or fauna. Some models ignored relatively small consumptive uses such as domestic, or livestock water, often reasoning that the volumes of such use are negligible, or they do not have reliable information (Teasley & McKinney, 2011). No study addressed all relevant economic sectors. Benefit functions related to wetland or other ecosystems were addressed by only a few studies (Ringler & Cai, 2006). Moreover, non-market ecosystem services including vegetation or forestation benefits due to groundwater recharge, sediment carrying by the river flow, and improved environmental benefits of water were not covered in any of the HEM studies reviewed. Furthermore, all the models used monthly time steps except Bekchanov et al. (2015a) who used six-monthly (April–September). In many cases, weekly or fortnightly temporal resolution could give more accurate results and would certainly be necessary to more closely investigate actual operational changes.

CONCLUSION
HEMs represent hydrologic engineering and economic systems. In addition to identifying possibilities to minimize costs or maximize profits, they provide a framework to consider the value of water services in the...
planning, design, and implementation of water management arrangements. It is a combination of engineering, economics, and hydrologic science, which fosters integrated water resources management (IWRM). HEMs can guide policymaking and reveal where innovative policies can replace an outdated system. The objective of the review was to look at how HEMs can suggest mitigating water sharing disputes among co-riparian countries on transboundary rivers. The comprehensive review met all the objectives. HEMs cannot resolve water conflicts in a shared basin, they can propose for the options of solution. The theory behind this study is the benefit sharing method which is supported by many authors. This review article diagnosed how the HEMs can resolve trans-boundary water dispute following the benefit sharing method.

More than 300 HEMs have been developed worldwide to improve river management. Yet, very few (only 25 that we could identify) focused on transboundary river water disputes. Benefit sharing, which has been proposed by many authors (McIntyre, 2015) as a strategy to mitigate water disputes, has not been fully explored by the HEMs to date. Though various types of benefits that were addressed by the HEMs, most HEMs that were reviewed focused on irrigation and hydropower which are benefits from the river, and very few studies focused on fisheries, environment, wetland which are benefits to the river. No studies explored out of river benefit sharing which involves compensation losses for values generated by water with benefits not related to water such as the provision of energy for losses of hydropower or provision of shorter transit routes through one country for more flow send to another country. International rivers can act as a catalyst among the riparian countries and thus can promote cooperation in trade, commerce, exchange of technologies, and other various fields. HEMs can play an important role in this regard and can be used to explore the possibilities for out of river trade. In the future, HEMs will be used to study optimization, trade-off, water transfers, and water-use efficiency. It is to be mentioned that HEMs can be used to evaluate options for the win-win solution of the water dispute. But chances of success depend on perspective. How politicians/diplomats can implement the options/results. More effort to include environmental and recreational values is needed. Finally, to make HEMs more accurate, more spatial and temporal disaggregation, more stakeholder participation, more real data rather than assumption would be beneficial.

DATA AVAILABILITY STATEMENT
All relevant data are included in the paper or its Supplementary Information.

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