Water **2015**, *xx*, 1-x; doi:10.3390/——

OPEN ACCESS

water

ISSN 2073-4441

www.mdpi.com/journal/water

Article

Agent Based Modelling for Water Resource Allocation in the Transboundary Nile river

Ning Ding [1], Rasool Erfani [2], Hamid Mokhtar [3] and Tohid Erfani [1]*

[1] University College London, Department of Civil, Environmental and Geomatic Engineering, London, UK
[2] Manchester Metropolitan University, Department of Mechanical Engineering, Manchester, UK
[3] The University of Melbourne, Department of Mathematics and Statistics, Parkville, Australia

* Author to whom correspondence should be addressed; t.erfani@ucl.ac.uk, +44 (0) 207 679 0673

Received: xx / Accepted: xx / Published: xx

Abstract: Water resource allocation is a process of assessing and determining a mechanism on how water should be distributed among different regions, sectors and users. Over the recent decades, optimal solution for water resource allocation has been explored both in centralised and decentralised mechanisms. Conventional approaches are under central planner suggesting a solution which maximises total welfare to the users. Moving towards the decentralised modelling, the techniques consider individuals as if they act selfishly in their own favour. While central planner provides an efficient solution, it may not be acceptable for some selfish agents. The contrary is true as well in decentralised solution, where the solution lacks efficiency leading to an inefficient usage of provided resources. This paper develops a parallel evolutionary search algorithm to introduce a mechanism in re-distributing the central planner revenue value among the competing agents based on their contribution to the central solution. The result maintains the efficiency and is used as an incentive for calculating a fair revenue for each agent. The framework is demonstrated and discussed to allocate water resources along the Nile river basin, where there exist eleven competing users represented as agents in various sectors with upstream-downstream relationship and different water demands and availability.

Keywords: Agent based problems; water resource allocation; Nile river; evolutionary algorithm

1. Introduction and background

Water scarcity, population growth and lack of proper resource allocation mechanism tend to cause regional instability [1]. A typical example concerns the northern African countries within Nile basin located in the most arid region of the world, where an unfair distribution of water resources is present for a long time. Introducing a fair mechanism for water allocation can help the region's economy and political stability. Standard water management approaches model the whole water basin as a centralised system and distribute water by a central planner (CP) to maximise the summation of all users' utilities [2,3]. The water in this mechanism is allocated to achieve the equal marginal return to water for all the users. This leads to an ambiguous interpretation of the aggregated problem; whether it proposes a planning strategy or simulates the market process [4]. Further, the CP ignores the selfishness of competing water users and assumes the best solution to the system would be accepted completely by all the participants. This leads to unsatisfactory results for some users with better accessibility to the resources asking for a higher revenue distribution. To address the idealisation and oversimplification involved in the water basin management issues, decentralised planning (DC) is introduced. [5] implement a priority based sequential algorithm for upstream-downstream water reallocation. Once the upstream user solves its own problem, the solution is included to the next downstream user's problem and this continues until all the individual problems are solved in sequence. The applicability of multi-agent systems have also been investigated in the field of environmental and natural resource management as reported by [6] and [7]. In this type of approach, each user is autonomous by itself and exchange information with other neighbour users within a system. An example of using a multi-agent system is developed by [8], and is further extended in allocation of water in yellow river basin [9] and is used to compare administrative and market based water allocation [10]. This approach considers all users as individual agents making decisions by interacting with each other and a coordinator who resolves the users' conflict in later stages. The method implements the modified penalty-based nonlinear program with a two-step problem. The first step finds a solution to all individual agents with possibility of constraint infeasibility and the second step is an optimisation model which reduces the constraint violation at the system level. In application, constraint infeasibility is explained as either the deficit or as an agent behavioural adjustment indicator for reducing the constraint violation [8]. From a game theoretical perspective, non-cooperative approaches have been examined in the systems in which users involve in a game to increase their pay-off, knowing that their decisions affect those of the other users. The approach provides insights for understanding water conflicts and is often implemented for the games with qualitative information about the users' payoffs [11]. Another approach to the above problems is developed by [4]. They use the multiple complementarity problems to express spatial externalities resulting from asymmetric access to water use for water right pricing. The individual optimisation problem is formulated for each user with the inflow quantity given as exogenous value to each problem as opposed to being a decision variable in centralised formulation, i.e. aggregated welfare maximisation. The price of the demanded water is used to clear the output market and the uniform wage rate is used to clear the labour market formulated as complementary constraints to the problem. To this framework, introducing extra coupling constraints changes the formulation to a more general problem framework namely, quasi variational inequality problem (i.e. a complementarity problem with shared constraints amongst the users [12]). The convergence of the algorithm is guaranteed upon the convexity assumption and continuously differentiable functions with diagonally dominant Jacobians [13].

Although the above decentralised tools and techniques satisfy the selfishness of each agent in maximising its utility function to achieve higher revenue, they lead to an inefficient solution from CP perspective. Therefore, it is desirable to follow the efficient CP solution but re-distribute the achieved revenue to the agents in a fair way; considering, of course, that the revenue is transferable between agents. To account for this, we define a notion of fairness based on each agent's contribution on achieving the CP solution. We calculate a unique solution with some favourable properties which guarantees the cooperation maintenance. To find the agent's impact on CP solution, as will be discussed in the next sections, we need to know the best response of each agent on the action of the other group of agents and vice versa, simultaneously. To realise this, we develop an evolutionary algorithm solving interrelated optimisation problems in parallel guiding the search towards a feasible solution in a distributed manner. This will guarantee that the contribution of each agent is properly captured for later fair revenue distribution.

Section 2 describes the background information of Nile water basin and identifies the problem to be addressed. The proposed methodology is outlined in Section 3. The Nile basin problem is dealt with in Section 4 and results derived from different mechanisms are discussed in Section 5. Section 6 summarises the findings and conclude the paper.

2. Problem identification: Nile River Basin

The Nile is the main vital water artery and the home to more than 160 million people in the North Eastern region of Africa shared by eleven countries [14]. It is 6853 kilometres in length and total area of its basin is over 3 million kilometres, covering about 10 percent of African continent [15]. There are two main tributaries: the White Nile and the Blue Nile, which are joined in Sudan 1.

The water contribution to the river varies greatly, from Ethiopia, which contributes the most water, to Egypt, which have no contribution to Nile water [16]. Yet, as the lower reaches of Nile basin are mostly arid or semiarid regions, some countries like Egypt and Sudan with a high percentage of total area of the countries show a strong dependency upon the Nile River [17] (Table 1). The unbalance between the inferior water availability and huge water extraction cause harmful consequences to basin stability and regional development. Hence, an adequate water supply is often considered as a question of national survival for many Nile riparian states [18].

The allocation of Nile water resource is complicated due to the combination of riparian's less rainfall and political inequality. The dependency to water resources shown in Table 1 is the degree to which the supply of a country's water resources is dependent on sources external to its political boundaries and can be calculated using the relation $(ARWR - IRWR)/ARWR \times 100$ [14]. As shown in Table 1, Sudan and Egypt rely on the external water resources to a great extent, in which over 95$\%$ of water stems from external sources. Overall, the water allocation within the basin is still unfair and unacceptable to many of states along the Nile River, specially to those upstream contributing the most to the sources.

3. Preliminaries and definitions for fair resource allocation

In this study, a fair and an efficient

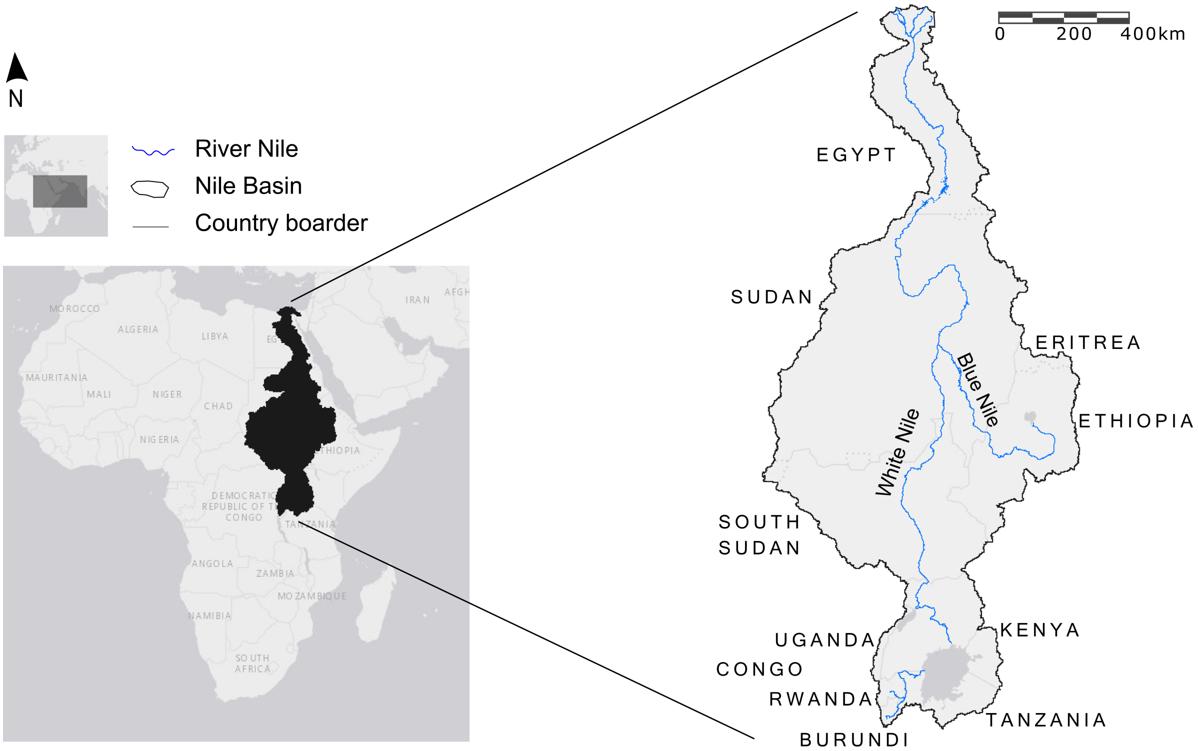

Figure 1. Nile river basin, its location and tributaries

Table 1. Utilisation of water diverted from Nile River among riparian countries [19,20]

Country	Internal water resources (IRWR)	Actual water resources (ARWR)	Dependancy Ratio	Diverted water from Nile	% of total Resources	Diverted for Use
Burundi	10.06	12.54	19.75	40.9	2.3	1.77
Rwanda	9.5	13.3	28.57	17.1	1.58	1.07
Tanzania	84	96.27	12.75	N/A	N/A	N/A
Uganda	39	60.1	35.11	11.4	0.46	0.18
Sudan	4.0	37.8	96.13	1074	58	56
S.Sudan	26.0	49.5	65.8	1074	58	56
Egypt	1.8	58.3	96.91	990	94.7	103
Ethiopia	122	122	0	76	4.56	4.27
Eritrea	2.8	7.315	61.72	124.0	N/A	N/A
Congo	900	1283	29.85	6.7	N/A	N/A
Kenya	20.7	30.7	32.57	74.85	8.91	7.05

resource allocation approach based on evolutionary algorithm (EA) is proposed. To retain the efficient centralised solution whilst the achieved revenue is fairly re-distributed among the agents, the impact each agent has on the whole system should be identified. In order to know the best response of each agent on the coalition of others, a parallel evolutionary algorithm is developed by [21,22] which enables the agents to automatically solve their local optimisation problem, cooperating with others and the whole system. To elaborate some key concepts mathematically, the preliminaries are as follows.

3.1. Preliminary and definitions Let $I = \{1 \dots n\}$ denotes a set of agents. Assume that each agent i controls vector $x_i \in \mathbb{R}^{n_i}$. Let x_{-i} be a vector containing the strategies (allocation) of all agents excluding that of the agent i. Each agent by receiving allocation x_i maximises his revenue via its utility function u_i. The utility u_i of the strategy profile $\mathbf{x} = (x_1, \dots, x_n) \in \mathbb{R}^n_+$ or in short $\mathbf{x} = (x_i, x_{-i})$ is $u_i(\mathbf{x}) = u_i(x_i, x_{-i})$. We define the followings.

Definition: (Central planner welfare maximisation (CP)) A solution is a social welfare maximisation or a central planner (CP) approach if it is derived by the following optimisation problem,

$$\mathbf{x}^* = \underset{\mathbf{x}}{argmax} \sum_{i \in I} u_i(\mathbf{x}), \tag{CP}$$

where summation is over all the utilities of the agents. This leads to a solution from an outside observer as if he/she is responsible for the values of all agents.

Definition: (Contribution to cooperation) Define $U^* = \sum_{j \in I} u_j(\mathbf{x}^*)$. Further, assume that agent i decides to leave the cooperation and act as a singleton (or in isolation) and let U^*_{-i}=$\sum_{j \neq i} u_j(x^*_{-i})$ be the summation of all other agent's revenue when i leaves them. We define agent i's impact on CP solution as,

$$\overline{u}_i = U^* - U^*_{-i},$$

which measures how much agent i contributes to CP solution.

Definition: (Fairness) A revenue re-distribution mechanism is *fair* if the revenue for each agent i follows the following equation:

$$u^r_i = \alpha_i \times U^*,$$

where,

$$\alpha_i = \frac{\overline{u}_i}{\sum_j U^*_{-j}}.$$

This means that each agent gets an allocation based on his contribution to the CP solution. This definition makes sense and has two indirect properties; (**a**) it is *budget balanced*; that is, the sum of all u^r_i equals the whole CP revenue value U^*, which in other words conveys that the mechanism collects and disburses the same amount of money from and to the agents; and, (**b**) it is *rational*; that is, no agent ever loses by participation (the revenue to each user is greater than zero). The above explains that the more contribution one agent has, the higher its revenue is. In this case, agents are encouraged to abide by the decision derived by CP problem ($\mathbf{x}^*$) if they are given a revenue following u^r_i values.

U^*_{-i} implies that agent i, which left the set of all agents, independently compete on the resources with agents $\{1, 2, \ldots, i-1, i+1, \ldots, n\}$. If agent i knew the others' strategies, his strategic problem would become simple; he would be left with the single-agent problem of choosing a utility-maximising problem. However, the two problems formed by agent i and agents $\{1, 2, \ldots, i-1, i+1, \ldots, n\}$ should be solved, simultaneously. This is because of the fact that agent i's best strategy depends on the interaction with the group he has left and which should not be ignored when finding U^*_{-i} values. Therefore, U^*_{-i} depends on the solution of two interrelated maximisation problems formed by agent $\{i\}$'s utility, u_i, and agents' $\{1, 2, \ldots, i-1, i+1, \ldots, n\}$ aggregated utilities, $\sum_{\substack{j \neq i \\ j \in I}} u_j(x_{-i})$ which should be solved at the same time. We will be using a parallel evolutionary technique defined next to deal with this two distributed problems.

3.2. Parallel search algorithm Here we formulate a general class of interrelated problems in which

their optimisation problems are simultaneously solved in parallel while interacting with each other. In a most general case and where n agents are solving their problems individually, each agent solves one optimisation problem and seeks its own optimal strategies while interacting with the others. More precisely, given $U : \mathbb{R}^n \rightarrow \mathbb{R}^n$ representing all n agents' utilities, we find $\mathbf{x} = (x_1, \ldots, x_n) \in \mathbb{R}^n_+$ by simultaneously solving the following n problems:

$$\begin{aligned} \underset{x_i}{\text{Max}} \quad & u_i(\mathbf{x}) \\ \text{subject to} \quad & \mathbf{x} \in X_i. \end{aligned} \tag{P_i}$$

where each agent i controls vector $x_i \in \mathbb{R}^{n_i}$ to optimise the utility (objective) function u_i subject to the constraints set X_i containing $\mathbf{x} \in \mathbb{R}^n_+$. The interrelation is explained as the objective function and the constraints in P_i depend on other agents' decisions.

To solve the n agent problems $P_i,\ i = 1, ..., n$ simultaneously, we dedicate each problem P_i to one agent i. Since there is interconnection between each problem due to vector $\mathbf{x}$, we solve each problem whilst it communicates with the other problems by sharing information. Lets call **P** the problem formed by all P_is. We use parallel genetic algorithm [23] and the idea of co-evolution [24] to solve **P** with an extension that each (sub-)problem P_i has its own objective function. This concept is used in [25] to gain faster convergence to Pareto solution in multiobjective optimisation problem. Let x_{-i} be a vector containing the decision variables of all agents involved in problem P_i excluding that of the agent i. The search algorithm is described by n different search trajectories performing in parallel through the following mapping H:

$$x_i^{t+1} = H(\overline{x}^t_{-i}, x^t_i, P_i),$$

where H shows the interconnection between the agents. H acts as a synchronization map for agent i to optimise problem P_i given the decisions of other interacting agents in its neighbourhood remain fixed shown by $\overline{x}^t_{-i}$. H describes that x_i value is updated by a search on problem P_i at generation t linking decisions x_i and $\overline{x}_{-i}$. Due to problem P_i, each agent knows its own problem components and hence by communicating with other neighbouring agents through H, it has local activity for exploring the search

Algorithm 1: Parallel search algorithm

```
1  Randomly initialise $n$ populations of size $m$ ($pop_i$);
2  Define $neighbours_i$ and set $nei_i$ = $|neighbours_i|$;
3  Set $MaxGen$;
4  while Not $MaxGen$ do
5      for $i$ = 1 to $n$ do
6          for $k$ = 1 to $m$ do
7              Randomly pick $p_{s1} \neq p_{s2} \neq p_{s3} \neq p_k$ from $pop_i$;
8              $p_b \leftarrow$ reproduction ($p_{s1}, p_{s2}, p_{s3}$);
9              if $f_i(p_b) \leq f_i(p_k)$ then
10                 $p_k \leftarrow p_b$
11         $pop_i^* \leftarrow$ The best individual in $pop_i$;
12     $\forall\, i, j = 1, ..., n,\ i \neq j,\ pop_i \leftarrow pop_j^* \wedge j \in neighbours_i$;
```

space. In what follows, we give details of the search algorithm to solve the agents problems in Algorithm 1.

Each agent i has a devoted search trajectory formed by a population of size m (Line 1). pop_i is a $m \times ne_i$ matrix and is populated randomly. ne_i is the number of interacting agents given by the cardinal of the set $neighbours_i$ (Line 2). In other words ne_i equals the number of neighbouring agents affecting the decision of agent i plus one. All individuals $p_k = (x_1, ..., x_{ne_i})$ in each population i undergoes a reproduction in each generation t of parallel searches (Line 8). At the end of each generation t, the neighbouring agents ($j \in neighbours_i$) share their best individuals to form the updated population for next generation $t + 1$ (Line 12).

where three populations are involved with $ne_i = 3$. As explained in the figure, each agent deals with problem P_i optimising for x_i. At the end of each generation t, pop_i^*, the best individual in pop_i based on its objective value, is obtained. pop_i^* migrates to the population of the neighbours and remain fixed for the next generation $t + 1$. This makes each agent at the end of each generation to be informed of the decisions of the other neighbouring agents involved in its own problem. Due to n different search trajectories, the algorithm allows independent search for agents by relying only on locally available information. This procedure leads to the evolution of separate populations over successive generations, and the convergence is assumed when the agents cannot further improve their objective function values f_i.

3.3. Resource allocation context As stated earlier, to find the contribution $\overline{u}_i$ of each agent i to the CP solution, we need to assure that the solution to agent i's utility maximisation is the best response to the solution of sum of utilities of the other agents and vice versa. To do so, we split the set I by removing one agent at a time from I to form two problems P_1 and P_2 for each instances. Specifically, problem P_1 is the utility maximisation for agent i (u_i) and problem P_2 is the aggregated utility maximisation for

Algorithm 2: Steps to redistribute utilities amongst self-interested agents

```
Find $U^*$;
for i = 1 to n do
    Solve problem $P_1$ and $P_2$ using Algorithm 1;
For each agent $i$, calculate $\overline{u}_i$, $\alpha_i$;
$u_i^r \leftarrow \alpha_i \times U^*$;
Distribute to each agent $u_i^r$;
```

agents $1, 2, \ldots, i-1, i+1, \ldots, n$ $(\sum_{\substack{j \neq i \\ j \in I}} u_j(x_{-i}))$. Problem P_1 and P_2 are then solved in parallel for each agent i using Algorithm 1. Algorithm 2 summarises the steps to obtain a fair resource allocation to different self-interested agents.

4. Nile river basin water sharing mechanism

Considering the major water utilisation of riparian and their geographic positions Figure 1 illustrated in Section 2, the water users located in the Nile riparian states are modelled as agents within a distribution network. The objective function for each agent is the economic outcome of its water abstraction shown by $a_i x_i - b_i x_i^2$. The economic function is a simple quadratic function calculated by integrating the linear water demand functions for each agent [21] (For details the reader is referred to [2,26,27]). All agents follow the upstream-downstream relationship, interconnecting with neighbours using the mass balance equations. The CP model aims at the maximisation of total benefit, and is formulated as a single optimisation problem with summation of all benefit functions as in Equation CP. Following Section 3.3, for the decentralised model, agent i is separated from the rest of the agents and its own economic function is maximised concurrently as the rest try to maximise their group revenue using Algorithm 1.

4.1. Water availability

The mean annual flow of Nile River in 2015 is 84 billion cubic metre (BCM) per year [28]. In this case-specific modelling, the minor water inflows and evaporative losses are considered negligible. Specific to the two tributaries, hydrological data at Mogren dam is chosen to represent average annual runoff of the White Nile (Q_1) and Khartoum monitors data of the Blue Nile (Q_2) [19]. In experimental set-up, therefore, Q_1=24.0 BCM and, Q_2=60.0 BCM based on the average hydrological data regulated at these stations [29].

4.2. Population and demand values

The objective function is the benefit function that quantifies the total benefit generated by water extractors from water use. In order to set reasonable value for the parameters a_i and b_i in objective function, the water demand curves should be estimated primarily according to the water demand and price, and then total benefit functions are calculated by integrating the demand functions. Following [2], the point expansion method is used to estimate the linear demand curve for various sectors [2]. The original point of expansion is based on the total water consumption and the water price. For simplicity, the marginal value of water is referenced as water price. Water consumption is obtained using:

$$Water\ demand = total\ water\ usage \times\ \%\ of\ population\ within\ the\ basin$$

Table 2 exhibits the factors determining the total water demand in the basin amongst agents.

Table 2. Water consumption within the basin [17,19]

Agent	Sectors	Population within the basin(million)	% of total population	Water usage (BCM)	Water demand with the basin(BCM)	Source
A	Agriculture	4.88	44.50%	0.22	0.0979	1
B	Agriculture	8.17	69.40%	0.1	0.0694	1
C	Agriculture	8.24	16.70%	4.632	0.7749	1
D	Agriculture	2.8	4.10%	0.11	0.0046	1
E	Industry	30.28	76.40%	0.12	0.0917	1
F	Agriculture	14.62	33.00%	1.01	0.3329	1
G	Energy	10	85.50%	0.21	0.1818	1
H	Agriculture	29.56	31.40%	5.204	1.6347	2
I	Agriculture	0.21	3.30%	0.29	0.0096	2
J	Agriculture	20	29.60%	6.56	1.9445	1+2
K	Municipal	51	62.20%	5.3	3.2941	1+2

The population within the basin, water usage for utilisation and their marginal values are the main benchmarks when determining the water demand curves, which are indirectly reflected on parameters setting in objective functions [14]. Based on Table 2, from agent A to K, **a** = [100, 100, 100, 100, 1860, 100, 13000, 100, 100, 100, 1300], and **b** = [511, 721, 65, 10960, 10139, 150, 35757, 31, 5200, 26, 197].

5. results and discussion

In both CP and decentralised solution procedure, $MaxGen$=100 in Algorithm 1, population size for each agent is set as m=50 and cross over and mutation is set as 0.5 and 0.7, respectively. Accounting for reliability, all the instances are run for 30 times and their average value is reported.

5.1. Centralised solution

In CP model, the fitness function is the aggregated benefit of all countries and, therefore, the problem is to search the maximum value of system revenue . The revenue of the whole system is reported as 3575.94 B. The benefits of each agent i in CP solution are shown in Table 3 along with the amount of water abstracted.

5.2. Decentralised solution

Eleven different model instances are solved where in each single instance, two problems are optimised in parallel using Algorithm 1. Table 4 reports the results.

Table 3. Water resource allocation results in centralised manner (CP). Burundi(A), Rwanda(B), Tanzania(C), Congo(D), Uganda(E), Kenya(F), S.Sudan(G), Ethiopia(H), Eritrea(I), Sudan(J) , Egypt(K)

Agent	A	B	C	D	E	F	G	H	I	J	K
Water (bcm)	0.1	0.04	0.54	0	0.08	0.17	0.16	1.24	0	1.72	2.85
Benefit (mGBP)	4.9	2.8	35	0	84.7	12.5	1159.5	76.3	0	95.1	2105.1
Total benefit	$U^* = \sum u_i^* = 3575.94$										

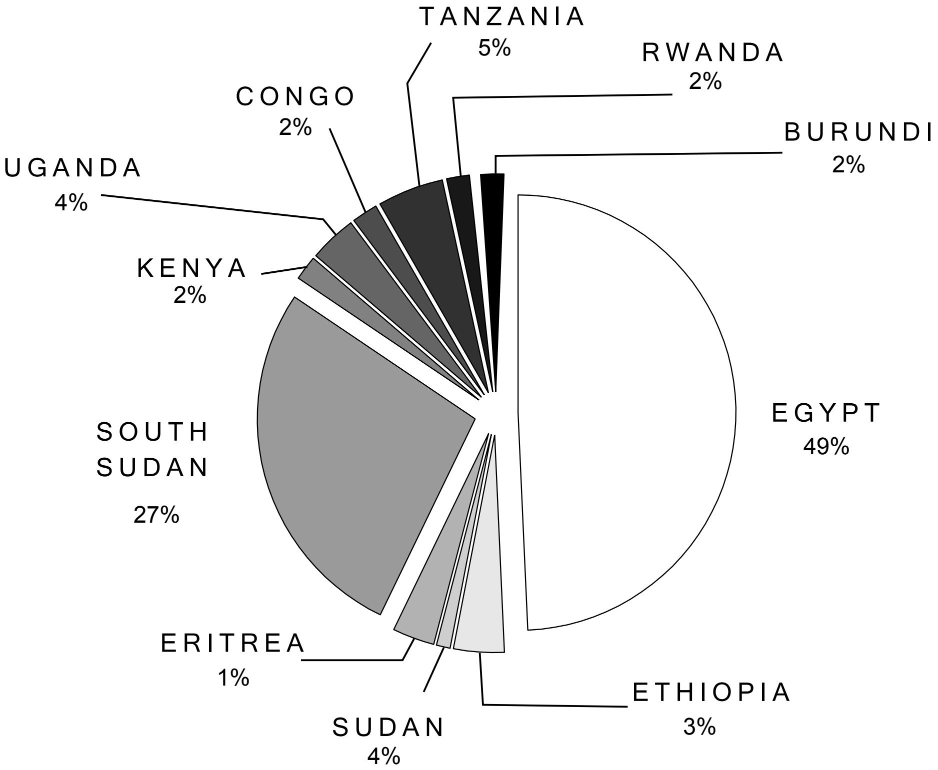

Figure 2. Percentages of contribution in cooperation

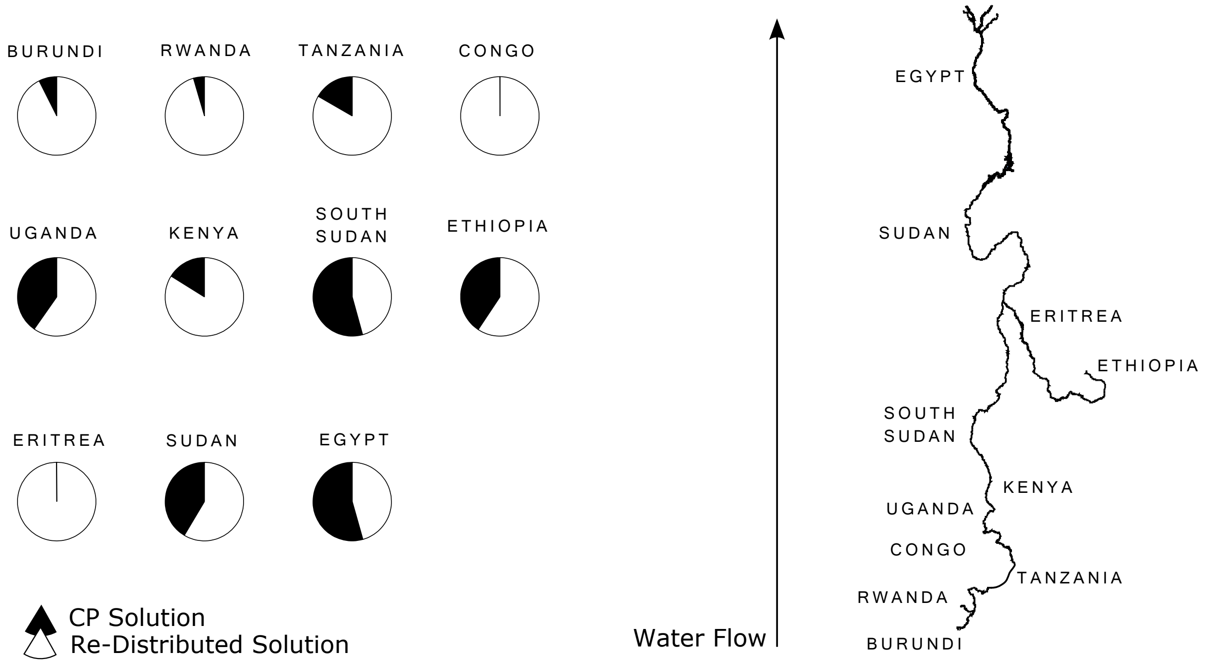

Figure 3. Revenue allocation results in CP solution and reallocation solution

5.2.1. Re-allocation solution

After finding the decentralised solution, from the perspective of fairness, we reallocate the system revenue based on the results derived from CP solution (Table 3). Figure 2 shows the contributions of each agent. The difference between the CP value and the group value of the rest in decentralised model embodies the impact one agent has on the whole system. Hence, the contribution is calculated, which provides the basis for revenue re-distribution. The incentive of agents in a cooperation game is determined by their location. The downstream users with high water dependency usually have higher incentive to join the cooperation. Figure 3 compares the decentralised solution with the CP distribution. For example, agent C contributes more than its upstream user B since it has less access to the water resource yet it requires more water resources. It can be seen that upstream location is beneficial to agents compared with the CP solution. Agent A, Burundi, who has the independent water resource as the upstream of White Nile tributary (Q_1), could increase its final obtainable benefit greatly from 4.9 to 61.16 in million pounds. This is the same for the other upstream users, while on contrary, the two main downstream water abstractors, agent G and K, are apportioned with less water after re-distribution. Through the rearrangement of water allocation, the upstream-downstream water disputes has the potential to be reduced. In addition, the distribution tends to be more evenly among agents than that in CP solution, which could be explained as the reflection of fairness to some extent.

6. Conclusion and future work

This paper seeks to address river Nile water distribution problem through a revenue re-distribution mechanism to achieve a fair resource allocation. The proposed framework leads to a final allocated revenue for each user which is proportional to its contribution to the basin. In centralised solution, aggregated benefits of all water users is used to search the optimal system revenue and in decentralised solution, a parallel evolutionary approach is developed to find the

Table 4. Water resource allocation results

Agent	Country	Parallel Problems	Contribution $\bar{u}_i$	Singleton P_1	Group P_2	Fairness α_i	Final Revenue u_i^r
A	Burundi	$\{A\}\{BCDEFGHIJK\}$	76.94	4.89	3499	0.017	61.16
B	Rwanda	$\{B\}\{ACDEFGHIJK\}$	75.94	2.802	3500	0.017	60.37
C	Tanzania	$\{C\}\{ABDEFGHIJK\}$	219.94	35	3356	0.049	174.84
D	Congo	$\{D\}\{ABCEFGHIJK\}$	86.94	0	3489	0.019	69.11
E	Uganda	$\{E\}\{ABCDFGHIJK\}$	157.94	85.09	3418	0.035	125.55
F	Kenya	$\{F\}\{ABCDEGHIJK\}$	81.94	13.01	3494	0.018	65.14
G	S.Sudan	$\{G\}\{ABCDEFHIJK\}$	1226.94	1168	2349	0.273	975.35
H	Ethiopia	$\{H\}\{ABCDEFGIJK\}$	139.94	76.37	3436	0.031	111.24
I	Eritrea	$\{I\}\{ABCDEFGHJK\}$	45.94	0	3530	0.01	36.52
J	Sudan	$\{J\}\{ABCDEFGHIK\}$	168.94	96.01	3407	0.038	134.3
K	Egypt	$\{K\}\{ABCDEFGHIJ\}$	2216.94	1947	1359	0.493	1762.35

contribution of each user to the whole system. The evolutionary algorithm is a parallel search where each user solve its own problem while in contact with the others. Re-allocation of revenue in this framework guarantees a fair and an efficient allocation of water to all users. Geographical location of users as well as their sector they are involved in (manifested via different marginal values) are the main factors affecting the final available revenue for water users which in turn determine their contributions. Compared with centralised solution, the results have taken into account the selfishness of individuals providing a fairer distribution of water to those with greater accessibility to the water. The revenue distribution mechanism introduced in this paper is a fair and unique approach but its stability requires further investigation. In addition, the algorithmic characteristics of the proposed framework still needs to be explored. Future research can analyse the technique for feasibility assurance and possibly faster convergence by using different operators and heuristics. In addition, since n instances of problems are independent from each other, a parallelisation scheme can be implemented.

Author Contributions

Ning Ding produced the first set of results and wrote part of the literature review and background of Nile river. She also calculated the economical benefit functions and code the Nile model. Rasool Erfani conducted the background research on agent based modelling and wrote part of the literature review as well as the algorithm section. Hamid Mokhtar worked with the others and helped the coding of the algorithm and he wrote part of the text. Tohid Erfani conducted the research, wrote the main part of the algorithm text, coded the algorithm and reviewed the manuscript with added references and background.

Conflicts of Interest

The authors declare no conflict of interest.

References

1. Speed, R.; Yuanyuan, L.; Zhiwei, Z.; Le Quesne, T.; Pegram, G. Basin water allocation planning: principles, procedures and approaches for basin allocation planning **2013**.
2. Erfani, T.; Binions, O.; Harou, J.J. Simulating water markets with transaction costs. *Water Resources Research* **2014**, *50*, 4726–4745.
3. Harou, J.J.; Pulido-Velazquez, M.; Rosenberg, D.E.; Medellín-Azuara, J.; Lund, J.R.; Howitt, R.E. Hydro-economic models: Concepts, design, applications, and future prospects. *Journal of Hydrology* **2009**, *375*, 627–643.
4. Britz, W.; Ferris, M.; Kuhn, A. Modeling water allocating institutions based on Multiple Optimization Problems with Equilibrium Constraints. *Environmental Modelling & Software* **2013**.
5. Wang, L.; Fang, L.; Hipel, K.W. Basin-wide cooperative water resources allocation. *European Journal of Operational Research* **2008**, *190*, 798–817.
6. Barreteau, O.; Bousquet, F.; Millier, C.; Weber, J. Suitability of Multi-Agent Simulations to study irrigated system viability: application to case studies in the Senegal River Valley. *Agricultural Systems* **2004**, *80*, 255–275.
7. Bousquet, F.; Barreteau, O.; d'Aquino, P.; Etienne, M.; Boissau, S.; Aubert, S.; Page, C.l.; Babin, D.; Castella, J.C.; Janssen, M.; others. Multi-agent systems and role games: collective learning processes for ecosystem management. *Complexity and ecosystem management: The theory and practice of multi-agent systems* **2002**, pp. 248–285.
8. Yang, Y.C.E.; Cai, X.; Stipanović, D.M. A decentralized optimization algorithm for multiagent system–based watershed management. *Water Resources Research* **2009**, *45*.
9. Yang, Y.C.E.; Zhao, J.; Cai, X. Decentralized Optimization Method for Water Allocation Management in the Yellow River Basin. *Journal of Water Resources Planning and Management* **2011**, *138*, 313–325.
10. Zhao, J.; Cai, X.; Wang, Z. Comparing administered and market-based water allocation systems through a consistent agent-based modeling framework. *Journal of environmental management* **2013**, *123*, 120–130.
11. Madani, K. Game theory and water resources. *Journal of Hydrology* **2010**, *381*, 225–238.
12. Heusinger, A.v. Numerical methods for the solution of the generalized Nash equilibrium problem. PhD thesis, Wuĺrzburg, Univ., Diss., 2009, 2009.
13. Kolstad, C.D.; Mathiesen, L. Computing Cournot-Nash equilibria. *Operations Research* **1991**, *39*, 739–748.
14. El-Fadel, M.; El-Sayegh, Y.; El-Fadl, K.; Khorbotly, D. The Nile River Basin: A case study in surface water conflict resolution. *Journal of Natural Resources and Life Sciences Education* **2003**, *32*, 107–117.
15. Kameri-Mbote, P.G. *Water, ConfliCt, and Cooperation: lessons from the nile river Basin*; Woodrow Wilson International Center for Scholars, 2007.
16. Mohamoda, D.Y. *Nile Basin cooperation: A review of the literature*; Number 26, Nordic Africa Institute, 2003.
17. HU, W.; YANG, J.; HUANG, H. A study of water resources development and utilization and management cooperation across the Nile River Basin. *Resources Science* **2011**, *10*, 003.

18. Hamouda, M.A.; El-Din, M.M.N.; Moursy, F.I. Vulnerability assessment of water resources systems in the Eastern Nile Basin. *Water resources management* **2009**, *23*, 2697–2725.
19. FAO Statistical Yearbook 2014 Africa Food and Agriculture. In *Food and Agriculture Organization of the United Nations Regional Office for Africa*; Accra, 2014.
20. Aquastat FAO. In *Food and Agriculture Organization of the United Nations*; FAO UN, 2015.
21. Erfani, T.; Erfani, R. Fair Resource Allocation Using Multi-population Evolutionary Algorithm. In *Applications of Evolutionary Computation*; Springer, 2015; pp. 214–224.
22. Erfani, T.; Erfani, R. An evolutionary approach to solve a system of multiple interrelated agent problems. *Applied Soft Computing* **2015**, *37*, 40–47.
23. Mühlenbein, H.; Schomisch, M.; Born, J. The parallel genetic algorithm as function optimizer. *Parallel computing* **1991**, *17*, 619–632.
24. Potter, M.A.; De Jong, K.A. Cooperative coevolution: An architecture for evolving coadapted subcomponents. *Evolutionary computation* **2000**, *8*, 1–29.
25. Lee, D.; Gonzalez, L.F.; Pet'riaux, J.; Srinivas, K. Efficient hybrid-game strategies coupled to evolutionary algorithms for robust multidisciplinary design optimization in aerospace engineering. *Evolutionary Computation, IEEE Transactions on* **2011**, *15*, 133–150.
26. Erfani, T.; Huskova, I.; Harou, J.J. Tracking trade transactions in water resource systems: A node-arc optimization formulation. *Water Resources Research* **2013**, *49*, 3038–3043.
27. Erfani, T.; Binions, O.; Harou, J. Protecting environmental flows through enhanced water licensing and water markets. *Hydrology and Earth System Sciences Discussions* **2014**, *11*, 2967–3003.
28. Understanding Nile Basin Hydrology: Mapping Actual Evapotranspiration Over The Nile Basin. In *Technical Bulletin from the Nile Basin Initiative Secretariat*; Nile Waters, 2015.
29. Sutcliffe, J.V.; Parks, Y.P.; others. *The hydrology of the Nile*; Number 5, International Association of Hydrological Sciences Wallingford, Oxfordshire, UK, 1999.

© 2015 by the authors; licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution license (http://creativecommons.org/licenses/by/4.0/).