Real-Time Water Resource Policies Supporting System for Decision-Making Based On GPU Application

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ABTRACT: Climate change is widely recognized to have an adverse effect on both short and long-term, especially under uncertainty of water resource availability. Water is not only affecting drinking and food availability, but also services and industrial manufacturing departments those are significant to our everyday-life. To retain water resource service under such an uncertainty and economics recession circumstance, governor has to determine an appropriate policy from a single or a combination of multiple demand-reduction and supply-increment options, which is not an easy task for the governor.

This paper describes designing of a system to answer the best water resource policy under a given constraint conditions, e.g. cost, ease to implement, social and economic scenario, etc. A final solution is determined from considering a vast of number of scenarios from all possible options combinations and uncertainty from climate change prediction, and give the best scenario back to governor in real-time. In each scenario, water resource equilibrium from predicted demand and supply in future is calculated, based on a given (generated) policy, economic and social effects on water shortage are determined.

A modern GPU computing and cloud computing technology are integrated in order to serve the most convenient experience to the system users. Adopting GTX-Titan GPU, the system could serve about 1,600,000 scenarios per minute, which is about several ten thousand times faster than the previous system framework. This enable governors using the system to make a decision on the fly.

KEYWORDS: water resource, policy, climate change, GPU

1. INTRODUCTION

Water is a limited vital resource and widely recognized by most of the nations that lacking of water in near future has high potential to be a severe problem not only in terms of volume, but also water quality, water distribution as a social problem. Such a problem seems to be oblique when we are sure that effects of climate change are already begun and definitely will at least affect our earth for several hundred years (IPPC, 2007).

Under economic recession situation and uncertainties of water supply and water demand in near future, governor has to determine an appropriate policy to yield the most benefit from lowest investment and impacts. The benefit is not only about having sufficient water in stock, but also satisfaction of citizen on the policy adopted. Most of the cases that the end-users are citizen, the solution to only the engineering issue could not solve the problem in reality, but the solution to social issue has to be pursued simultaneously. The more water in stock does not mean better, this can cause problem in area having high potential of flooding. On the other hand, investment refers to monetary aspect and time cost from planning to maintenance. The last term, impacts, has broad meanings those could be economical, environmental, social, etc.

To find an appropriate policy, it is necessary to know the situation of water in future. Climate change has a global effect on both physical and social aspects. The physical aspect is, as widely recognized, on changing of precipitation pattern and amount, which is directly affects the amount of water in river, dam, as well as underground water. As a result, the extreme condition can cause drought and flood disaster. On the other hand, the social aspect is on the cognition of citizen, which drive their behavior on water usage (water demand) as well as on consensus about water resource policy made by governor.

Drought is the event when water demand goes over water supply, which lead to a period of water shortage in corresponding area. In Japan, when amount of water resource is insufficient, water supply will be deducted step-by-step by each of water users sector starting by deducting industrial sector in the first step and then all the following sectors altogether: agriculture, commercial & service, household, etc. (Pongsak, 2012) When water resource is deducted in a specific sector, their economic activities will be reduced or stop, which causes the economic damage. When considered the supply chain by interregional Input-Output table (IO-table), the economic unit in lower supply chain will cause continuous economic damage in subsequence.

On the other hand, flooding is the event that water supply exceeded the water drainage capacity of the area. Damage area is decided by geographical feature, manmade structures, water drainage infrastructures, and human activities. Flood water level, flood area, flood period, and land-use conditions will determine the amount of economic damage sequence.

The authors started the first phase of research with drought and will continue to the second phase on flood later on. The contents hereby will be discussed only on the drought side. We selected Yoshino river basin in Shikoku Island, Japan, as a study area for the first phase.

As described above, the drought is caused by balance of water supply and demand. The policy is made will aim to reduce the effect of water shortage and effects and impacts of the policy need to be determined, Figure 1.

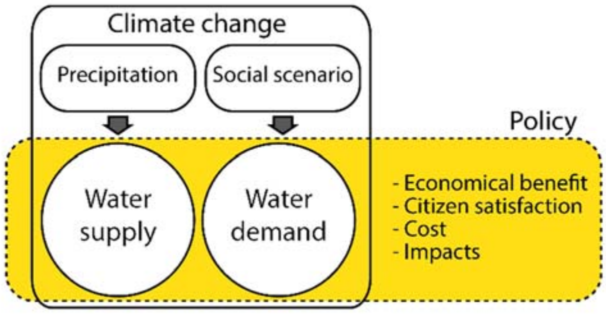

Figure 1. Relation on climate change, water supply, water demand and policy in drought scheme

The water resource policy can be made from implementing increasing water supply options, decreasing water demand options or both (Pongsak, 2012). Table 1 and 2, for example, shows a list of common policy options for drought scheme in Japan.

Table 1. Common water supply options

Water supply options
- Construct new dam
- Repair and improving existing water infra.
- Construct inter-basin water transfer facilities
- Maintain agriculture irrigation canal
- Construct desalination plant
- Change reservoir operation rules
- Adapt rainwater collection system
- Etc.

Table 2. Common water demand options

Water demand options
- Tap water pricing
- Water buy lease sell and water rights sharing
- Develop effective water saving awareness
- Distribute handbook in case of emergency

-	Regional disaster prevention and database
-	3R
-	Compromise stakeholder
-	Establish monitoring control system
-	Promote water saving equipment
-	Etc.

Each option has different effects on water demand and supply in each water user sector, satisfaction of citizen, implementation and maintenance cost, life span, etc. The options in reality are not simple as shown in table 1 and 2. Each option may contain sub-option, such as tap water pricing may contains +3%, +5%, or +10%, which make the number of overall options to be considered ever higher. It is difficult for governor to choose one or multiple options to fit their jurisdiction in the future, especially when large uncertainty exists in climate change phenomena and changing of social structure. Combination of feasible options (so called policy scenario hereby) under a predicted water resource condition can be as large as several million, which is nearly impossible to find out the best policy without effective tool.

Moreover, the tool is expected to be used in the situation that the solution should be evaluated speedily, which is an advantage to the governor (as a user) to decide the best policy while varying a number of constraints.

This paper introduces a system framework that is able to find a best policy from all possible combination of options based on given constrains in near real-time. At each policy, economic impact, social effects (citizen satisfaction) on water shortage (daily basis) are determined. Graphics Processing Unit (GPU) is utilized for massively parallel computing to meet such requirements.

2. EVALUATION OF WATER RESOURCE CIRCUMSTANCE IN FUTURE

This section describes the procedures to calculate effects and impacts of a given policy.

2.1 Balance of water resource

Amount of water balance at a day in future is calculated from predicted water demand subtracted by predicted water supply in the future. The positive value of the water balance indicates water shortage condition. A proper policy needs to be made to remove or reduce such water shortage amount or period as much as possible, figure 2.

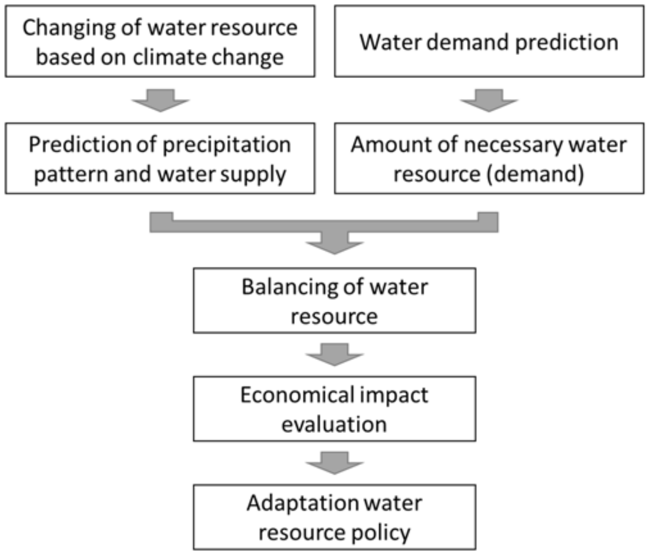

Figure 2. Balance of water resource and policy

The overall flow of the water supply calculation is shown in figure 3. Starting from selecting Global Climate Model (GCM) of the whole globe climate model prediction (CMIP3). Eight GCMs are selected as good representing of behavior of rainy season. These GCMs are then calibrated with observation data in the past and then perform bias collection for prediction in the future. WEB-DHM (Water and Energy Budget based Distributed) as a hydrological model was used to calculate river runoff and other hydrology parameters from a given precipitation data (and others) acquired from GCMs.

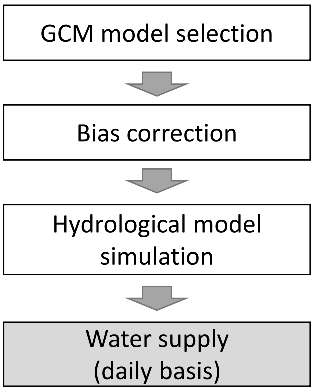

Figure 3. Procedures to obtain water supply in daily basis

Water demand in the future is predicted from IO-table that can acquire water resource in each water user sector. In addition, changing of economic growth and population is also considered as a social scenario.

2.2 Economic impact

Economic damage (Japanese Yen) per each water user sector due to drought (m^3/year) is calculated by the following equation.

$$\mathbf{D}_{econ} = \sum_{i=1}^{n} \alpha_i \sum^{t} W_d^i - W_s^i \qquad \textbf{Eq. 1}$$

Where D_{econ} is economic damage during period of time *t*, says a year. W_d^i and W_s^i are water demand and supply of sector *i* in daily basis, respectively (m^3/s). α_i is economic damage factor of sector *i* (Yen/m^3). *n* is number of water user sectors.

Economic damage factor α_i for each sector can be acquired from inter-regional IO table that is integrated with water account. Figure 4 shows the simplified version of IO table of the Yoshino river basin (YSN) and the rest of Japan (RoJ) for four sectors (Agriculture, Manufacturing, Tap water or household, and service). The added last row is integrated to the original OP table concept to link the water amount usage to the economic activities in each sector.

In the drought condition where demand has to be deducted to be fit within available water supply, value added as the economic production indicator reduces proportionally. The reduction of value added per amount of water demand then calculates the economic damage factor.

2.3 Citizen satisfaction

Citizen satisfaction is a 5-level index (the most negative to the most positive level) that evaluates the satisfaction of citizen on water resource on three aspects: water utilization, flood control, and water environment. Figure 5 shows a consciousness logic

Economic part: 10^11JPN			Intermediate demand								Final demand		Exports	Imports	Total output
			Yoshino river basin [YSN]				The rest of Japan [RoJ]				YSN	RoJ			
			A	M	T	S	A	M	T	S					
Intermediate input	YSN	A	0	1	0	0	0	1	0	0	0	0	0	-0	2
		M	0	8	0	4	1	12	0	8	6	5	7	-10	40
		T	0	0	0	0	0	0	0	0	0	0	0	0	1
		S	0	4	0	11	0	3	0	5	41	11	1	-1	77
	RoJ	A	0	1	0	0	16	76	0	13	0	43	1	-23	128
		M	0	9	0	5	26	1,414	6	642	19	935	557	-581	3,032
		T	0	0	0	0	0	8	5	42	0	26	0	0	81
		S	0	5	0	8	18	598	21	1,597	29	3,782	174	-109	6,124
Value added			1	13	1	47	68	919	48	3,818					
Total input			2	40	1	77	128	3,032	81	6,124					
Water demand: MCM			470	345	236	21	54,196	10,557	13,764	1,756	246	11,514			

Note: A is agriculture; M is manufacturing; T is tap water; and S is service

Figure 4. Inter-regional IO table model integrated with water account in Yoshino river basin

model for citizen satisfaction on water resource, which is constructed based on the recognition map generated by interviewing, Uemoto 2011. Each box in the figure is evaluated by the 5-level index, while the leftmost elements are the satisfaction of citizen and the rightmost elements are input to the human mind.

Based on this logic model structure, questionnaires are made to several hundred people to find the relation and strength of each element (using Gaussian Kernel method).

The logic model map is divided into 5 levels from the rightmost column and leftmost column where the input information started from the rightmost elements. The later columns from the rightmost are knowledge, recognition, intermediate outcome and final outcome as the satisfaction.

Each element in column level are linked be several arrows having balancing weights that obtained from the Kernel method. Giving 5-level

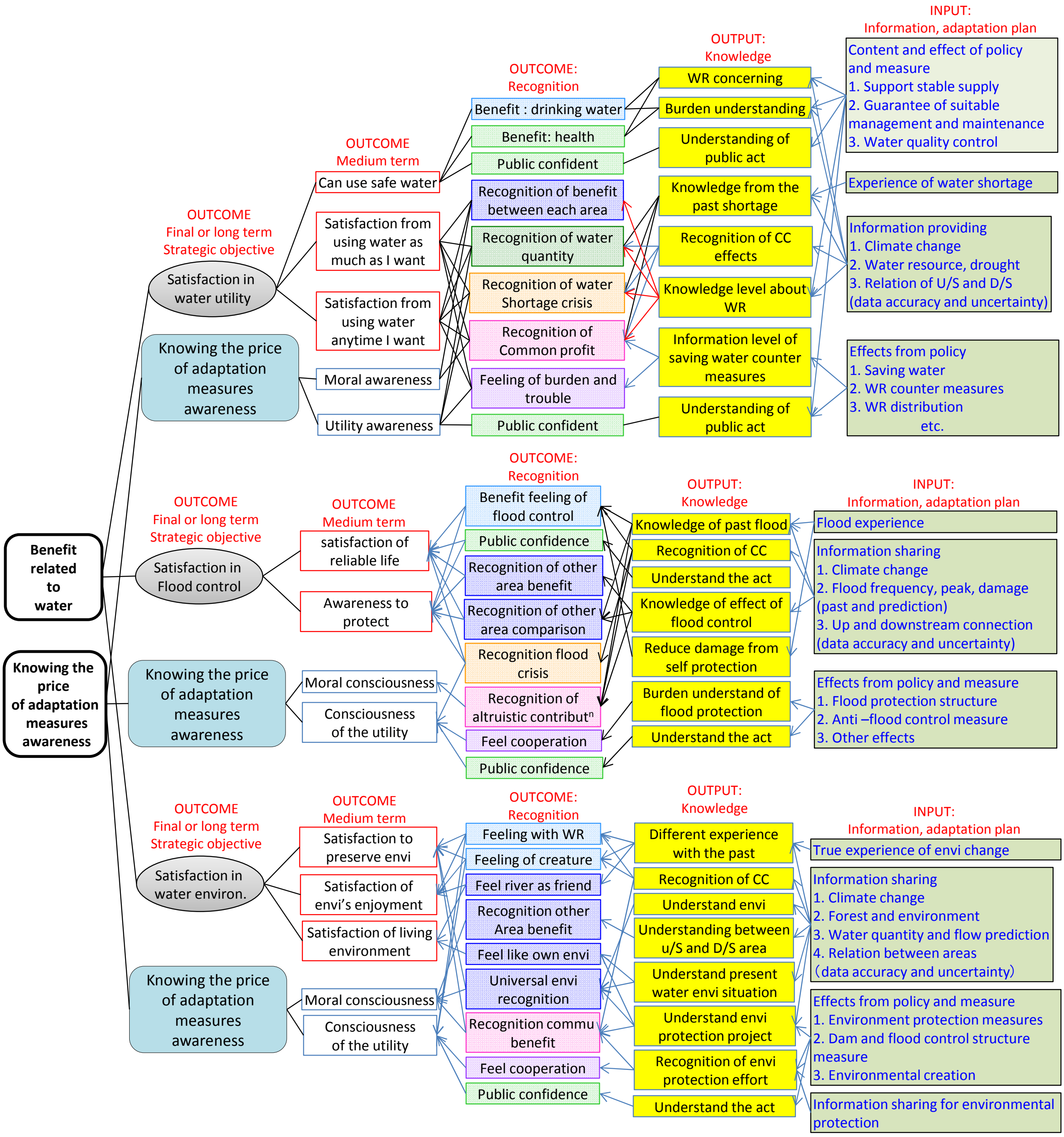

Figure 5. A consciousness logic model for citizen satisfaction in water, Uemoto 2011.Figure 4.

index to the input elements will calculate (weighted summation) again the 5-level index to the output element the adjacent left column level linked by weighted arrows. The 5-level index from the leftmost column level as final satisfaction indicator.

2.4 Water resource policy

As described in the previous section that the policy is categorized in to two schemes, water supply and water demand options. As for the policy options for drought side, demand options has effect to reduce water demand from water user sectors. On the other hand, water supply options have effect to increase amount of water supply under a given precipitation condition. As to simulating the effect of policy options, two operators (p_1^i *and* p_2^i) are introduced to do a simple mathematical calculation as shown in the following equation.

$$W_2 = \sum_{i=1}^{n} \left(W_1^i * p_1^i + p_2^i \right) \qquad \text{Eq. 2}$$

Where W_2 is total water demand or water supply in daily basis after a corresponding policy is applied (m^3/s), W_1^i is water demand or water supply of a sector *i* before applying policy (m^3/s). p_1^i is a multiplication factor to W_1^i, which is considered as a relative amount effect (-). For example, a 3R policy that aims to reduce 5% of water demand in sector *i* has p_1^i = 0.95. p_2^i is an additional-reduction term for sector *i*, which add or subtract absolute amount of water from W_1^i (m^3/s). For example, a new dam construction giving additional 0.03 m^3/s has p_2^i = 0.03.

In addition of the effects of policy in water resource control, each option also has other parameters such as fix cost, running cost, maintenance cost, etc. affiliated to.

When a policy is applied the economic damage can be evaluated by replacing W_d^i and W_s^i in Eq. 1 with W_2 by Eq. 2 correspondingly.

3. SYSTEM DESIGN

3.1 General concept

The concept to calculate economic impact, citizen satisfaction, cost for a given water resource policy is described in the section 2. In this section, we will discuss about generation all possible combination of options and evaluate effect and impact of each policy to find some candidate policies that are considered to be the best solution under a given constraints and scenarios.

The concept of the policy is really simple. The followings are the procedures for an individual policy evaluation.

1. Pick some options to form a set of policy
2. Calculate water demand and supply
3. Calculate water shortage amount and water deduction amount by sector
4. Evaluate economic damage
5. Evaluate satisfaction
6. Calculate other policy specific parameter, e.g. cost

On the other hand, there is another important element needs to be considered here, the policy generation. The concept is to find all possible combination of options as a huge set of policies, and each of them is evaluated by the procedures mentioned above.

Figure 6 show the overall calculation layers (loops) of the system framework. Based on a given target area (the outermost loop) and social scenario (the second loop), all possible policies are generated. For each generated policy, the parameters in the above procedures are generated for every points (daily basis) in time axis and every CGMs. The CGMs loop represents an uncertainty in water supply, while the social scenario loop represents an uncertainty in water demand.

After the calculation in the time loop is ended, economic damage, satisfaction and other policy specific parameters are evaluated for each GCM input. Once all GCMs results are calculated, statistically data are taken, and the candidate results are stored.

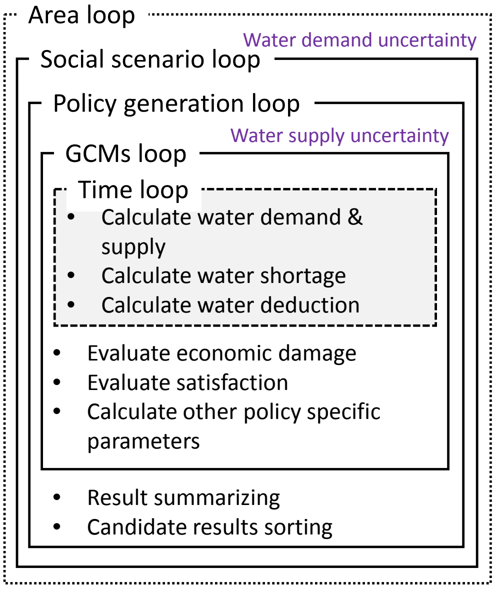

Figure 6. Overall calculation layers

All items in the figure 6 are the works that needs to be calculated. Most of the system in the world performs calculation by computer (specifically CPU). This is because CPU calculation has long and mature development, and easy for programming. The modern PC has 4, 6 or even 8 cores, which means the calculation can be done simultaneously at maximum the number of cores (except using Hyper-threading technology). The parallel computing technology has drastically changed since the birth of general purpose GPUs (GPGPU). GPU is a graphic processing unit that responsible to calculated what to display on PC monitor. Due to the needs of GPU to display complex 3D models such as in 3D CAD or 3D games, the development of multicore GPU is more advanced than the CPU. In 2005, GPU has been given the new task other than doing graphic things, i.e. general calculation. GPU can be used to perform a simple arithmetical calculation but in a massively parallel way. Comparing number of cores (number of simultaneously performable task) of the modern GPU to CPU, GPU has several orders many cores than those of CPUs, e.g. the modern GPU GTX-Titan for gaming has 2,688 cores. That means we can use GPU to process daily water data of 7.3 years in one cycle.

However, it does not means that we can use GPU to do every tasks in figure 6 for the maximum performance. The critical cons of the GPU are it cannot communicate with user and file stream. But what the system does is, interact with user, read input data from files, etc. These CPU specialized task will not be given to GPU. The way to design the system to achieve the maximum performance is to distribute proper tasks to the proper processing units.

Figure 7 shows the data flow from user through user interface to CPU and then to GPU. Data storage store files that needs for calculation, host memory is a temporary storage for CPU to perform calculation. For the calculation on GPU, data needs to be transfer from data storage to the host memory and then send to the memory on GPU device, called device memory. The process to transfer data from host memory to the device memory is very long latency. It is better for the most of the simple calculation tasks to be calculated by CPU than sending to GPU, since data transfer will take much time (100 times) and give unacceptable overhead in calculation time.

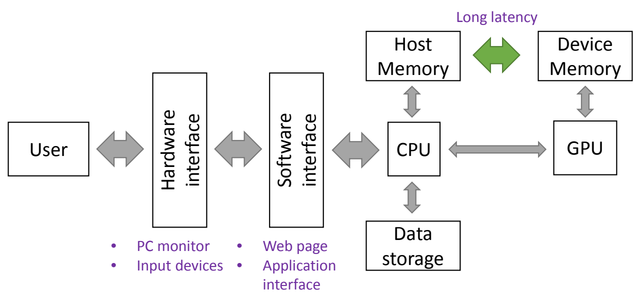

Figure 7. Data flow among user, CPU, and GPU

Considering the maximizing calculation

performance by minimizing data transfer between host and device memory, the calculation tasks in figure 6 are distributed to CPU and GPU as shown in figure 8. All loops except the time loop that are suitable for massively parallel computing, are assigned to CPU, and other tasks to GPU. The characteristics of the tasks assigned to GPU are summarized as in the followings.

1. Tasks in time loop on time axis are independent, simple arithmetic calculation and routine
2. All result can be stored in the device memory without transferring back to CPU unless all calculation is ended
3. Data necessary for calculating in GPU from the start to end can be transferred to device memory at once at the beginning of the calculation.
4. All effective results can be store in device memory until the end of the whole calculation.

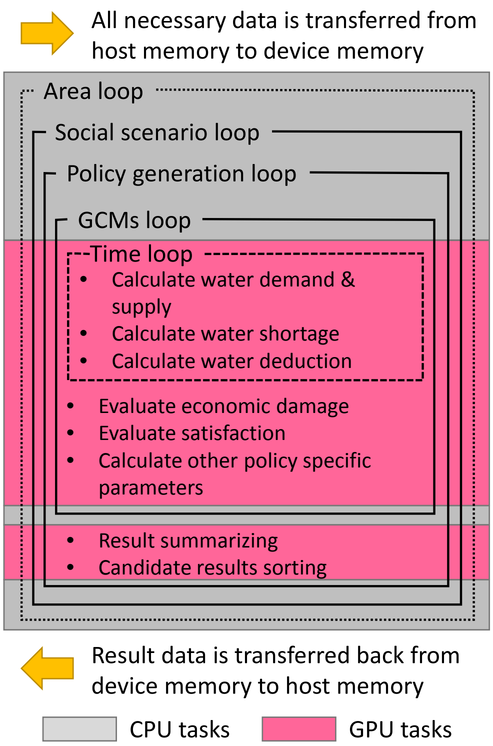

Figure 8. Tasks distribution between CPU and GPU

The issues 3 and 4 are the most important point to maximize the performance of calculation.

The data in device memory for each GCM loops contains, water shortage (daily time history), water supply after deduction rule in sector (daily time history), economic damage (yearly time history), no. of drought days (yearly time history), water shortage amount (yearly time history), cost, satisfaction, etc. Since there is a large amount of data per each CGM and policy needs to be kept in device memory. For example, if each loop needs 0.5 MB to store data, 3 million scenario loops need 1,500 GB of memory to lies in. However, the modern GPU has only 6 GB of memory, i.e. no way to store all data in memory. It is also impossible to relay these data to larger storage, e.g. HDD, since even the fastest SSD storage has just 1/1000 of speed of device memory.

The problem is not at only on the memory limitation. Let says if we can store all these 3 million scenarios of data fit into device memory, some candidate scenarios (e.g. the best three) when sorting by cost, no. of drought days, satisfaction, etc. need to be sorted by at most 9×10^{12} cycles of sorting operation by each sorting variable to be done. This is expected to be comparatively long processing time compared with calculation time, which makes merits of using fast GPU for calculation gone.

The strategy for finding candidate scenarios (policies) considered the solution to the mentioned problems are listed as in the followings.

- Use GPU threads for sorting only number of necessary candidates while discard the non-candidate data.
- Each GPU thread responsible for each sorting variable.
- Sorting process is done at every GCM loop level. This is to reducing sorting whole data at the end of calculation to sorting only candidates at every loops.
- The time history (both daily and yearly

basis) data are not stored. But will be calculated again when candidate scenarios are decided.

3.2 Policy generation

Water policy options shown in table 1 and 2 can be written in general formats as illustrated in figure 9. Each option in table 1 and 2 is analogy to the major options (Opt. *i* in figure 9). Each major option may contain sub-options, so-called minor option hereby (Sub. *i.j*).

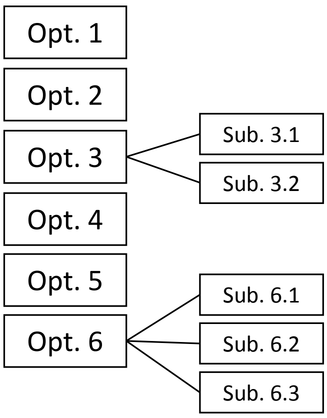

Figure 9. General format of the options

In the policy generation, the combination of options should contain only different major option, e.g. opt. 1 + opt. 3 + opt. 4 are valid combination. But if the options in the same major option are in the same combination, this is not good, e.g. opt. 1 + opt 3.1 + opt. 3.2. Therefore, major options and minor options need to be considered in two levels preventing the repeating of the minor options in the same major options.

In the policy generation loop, only major options are considered using combination algorithm. A number of policy to be implemented simultaneously, *r*, is varied from 1 to 7. Given *n* as a number of major options available. The total number of combination generated is

$$\sum_{r=1}^{7} {}^{n}C^{r} \qquad \text{Eq. 3}$$

For the combination that one of the option has two or more minor options, that combination will be looped through all minor options and generated for derived combination. Thus the number of total combinations of options given cannot be calculated directly as in the Eq. 3 without finishing all policy generation loops.

4. RESULT AND CONCLUSIONS

The system was tested with tentative 16 major options (some containing minor options), as shown in table 3.

Based on the Eq. 3, number of major combinations when n = 7 is 26,332 scenario to be calculated per GCM. When considered both major and minor options in combination process, about 400,000 combinations are generated per GCM, which is about 15 times of the number of pure combination of major options. If number of sub-options (minor options) in consideration increased, the number of total combination per GCM increases rapidly. We have tested the system by using 8 GCMs, which bring total about 3,200,000 time loops to be calculated per a given social scenario. Length of time history data for demand and supply was 20 years (= 7,320 operations per time loop), and each time loop contains 4 sub loops for calculating water demand, water supply, water shortage and water deduction. This means, for a specific area, a specific social scenario, at least $7320 \times 3200000 \times 4 = 9.4 \times 10^{10}$ loops need to be executed. This is excluding calculation of economic damage, evaluating satisfaction and calculation for other policy specific parameters, result candidate sorting, and policy generation process.

Table 3. Available water policy options for system benchmark

Option category	Opt.	Sub.	Option Name	wdp1_1	wdp1_2	wdp1_3	wdp1_4	wdp1_5	wdp2_1	wdp2_2	wdp2_3	wdp2_4	wdp2_5	wsp1	wsp2	fixcost	varcost
				(-)	(-)	(-)	(-)	(-)	(m3/s)	(m3/s)	(m3/s)	(m3/s)	(m3/s)	(-)	(m3/s)	10^6 Yen	Yen/m3
s	1	1	Construction of new water supply such as dam pond. Opt1								0.03	0.07				9031.64	91
s	1	2	Construction of new water supply such as dam pond. Opt2												0.18	18350	66
s	1	3	Construction of new water supply such as dam pond. Opt3								0.03	0.07				16350	164
s	1	4	Construction of new water supply such as dam pond. Opt4												0.18	33360	120
s	2	1	Repairing and improving existing water												0.1	0	44
s	3	1	Construction of inter-basin water transfer faculties						11.3		1.35	3.15				95000	4
s	4	1	Maintenance of the agriculture irrigation canal and promotion of the prevention of the tap-water leakage								0.07	0.15				0	522
s	5	1	Construction of desalination plants. Opt1								0.14	0.32				34700	282
s	5	2	Construction of desalination plants. Opt2								0.03	0.07				35060	352
s	5	3	Construction of desalination plants. Opt3								0.09	0.2				72960	160
s	6	1	New reservoir operation rule curves. Opt1													0	0
s	6	2	New reservoir operation rule curves. Opt2													0	0
s	7	1	Rainwater collection system. Opt1									2.22E-07				0.08505	608
s	7	2	Rainwater collection system. Opt2									1.64E-07				0.063	608
s	7	3	Rainwater collection system. Opt3									9.9E-08				0.0378	608
d	1	1	Pricing policy: +5%								0.03	0.03				0	0.05
d	1	2	Pricing policy: +10%								0.06	0.06				0	0.1
d	2	1	Water buy lease sell and water rights sharing: Agr													0	0
d	3	1	Develop effective water saving awareness									0.05				0	0
d	4	1	Handbook: Emergency plans during drought such as alternate day watering schedules									0.01				0	0
d	5	1	Database: Regional disaster prevention plan and									0.05				0	0
d	6	1	3Rs policy: 100 % of Max possible recycle rate		0.95											0	152
d	6	2	3Rs policy: 50 % of Max possible recycle rate		0.975											0	152
d	7	1	Cooperation among each stakeholders such as up and downstream									0.03				0	0
d	8	1	New establishment of the monitoring control system									0.01				0	0
d	9	1	Promotion of water saving equipment: Water-saving devices									0.05				0	20

s = supply, d = demand

wdp and wsp are corresponding to p_1 and p_2 effect parameters in Eq. 2

We have tested the system on a single GTX-Titan GPU having 2,688 cores. It can process about 1,600,000 time loops per minute, which means all 3,200,000 scenarios from the total combination of the options in tables 3 can be completed in about 2 minutes. It is considered to be not too long for the system user (governor) to specify constraints and wait 2 minutes for each run. The purposed system framework and design strategy are innovation to the water resource management field, which may bring more advantage to the future development.

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