Management of water resources assessment for nuclear power plants in China

Xiaowen Ding, Wei Wang, Guohe Huang, Qingwei Chen and Guoliang Wei

ABSTRACT

To deal with global warming and energy shortages, the nuclear power industry has flourished in China. Operation of a nuclear power plant consumes a large amount of water and discharges radioactive wastewater into nearby water bodies. Therefore, assessment and management of water resources are crucial for such projects. This article proposes the contents, procedures and methods of water resources assessment for nuclear power plants in China. Taking a pioneering inland plant as an example, a case study was also developed. It was suggested that assessment of water resources for a nuclear power plant in China should focus on regional water resources analyses, rationality of water-draw and water use of a plant, feasibility of water sources and impacts of water-draw and wastewater discharge on regional water resources. The proposed processes mainly included site survey and data collection, work outline completion and approval, water resources assessment, assessment report completion, expert consultation and public participation, and technological review, as well as administrative approval. The methods presented were referring to legal documents, site survey, model simulation, expert consultation and public participation. Finally, suggestions, including comparing and selecting several optional sites, improving impact assessment of radioactive wastewater discharge and enhancing public participation, were also proposed.

Key words | nuclear power plants, wastewater discharge, water-draw, water resources assessment, water use

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INTRODUCTION

To meet the demands of energy supply and greenhouse gas emission mitigation, the People's Republic of China (PRC) has implemented policies of adjusting energy structures (Chen *et al.* 2009) and exploiting new energy sources (Wang 2009). Among the new energy sources, nuclear energy is considered as the most effective and sustained way to deal with energy problems in China (Sovacool 2008; Jasmina *et al.* 2012). Therefore, China issued *The Medium and Long-term Development Plan of Nuclear Power (2005 to 2020)* in 2007 to promote the nuclear power industry (Zhou 2010). Even after the Fukushima Dai-ichi nuclear power plant accident, China issued *The 12th Five-Year Plan and 2020 Vision of Nuclear Safety and Radioactive Pollution Prevention and Control* in October 2012 (National Nuclear Safety Administration of Ministry of Environmental Protection of the PRC (MEP), National Development and Reform Commission of the PRC, Ministry of Finance of the PRC National Energy Administration of the PRC, Commission of Science Technology and Industry for National Defense of the PRC 2012). In the meantime, China decided to restart the construction of nuclear power plants (China's State Council 2012). The operation of a nuclear power plant consumes a large volume of water and discharges much radioactive wastewater into nearby water bodies. For such projects with significant impacts on water resources, water resources assessment (WRA) is a professional evaluation required by law in

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China in the early phase. In China, WRA is an exact term: it exclusively refers to the comprehensive analysis and assessment of the rationality of water-draw, water use and wastewater discharge as well as the impacts on the regional water environment and other water users of a designated project (new, reconstruction or expansion of an existing power plant), based on river basin or regional comprehensive planning and water resources special planning. Therefore, WRA and management of nuclear power plants are critical to both water resources conservation and to sustainable development of the nuclear power industry.

Research related to WRA for nuclear power plants has been carried out in several countries such as Canada, the USA, France and China. As for water-draw, recommended values for different types of reactors have been proposed, even for those under construction. Values for the AP1000 (Advanced Passive Pressurized Water Reactor 1000) reactor provide an example – the suggested water-draw amounts for an inland plant was between 0.96 and 1.27 m^3/s·GW (United States Nuclear Regulatory Commission (NRC) 2009; Changjiang Water Resources Commission 2009; Wuhan University of the PRC Hubei Xianning Nuclear Power Plant 2009a, Wuhan University of the PRC 2009b). With respect to water use, Khamis & Kavvadias (2012) stated that a nuclear power plant adopting an indirect cooling water system generally consumed 20 to 83% more water compared with a coal-fired plant of the same capacity. The volume required for a nuclear power plant using an indirect cooling water system was regarded as approximately 35 to 65 million liters per day for various types of reactors. Requirements and standards for water-draw, water use, wastewater discharge and their impact assessment of nuclear power plants also have been constituted on the basis of the research. In the USA, NRC (1984) required that an assessment of the impacts on the flow of the river, stream and riparian ecological communities should be carried out if a nuclear power plant took make-up water from a river whose annual flow rate was less than 9×10^{10} m^3/y. In Australia, it was suggested the maximum amount of cooling water use for a nuclear power plant with an indirect cooling water system should be 0.76 m^3/s·GW (Woods 2006). Besides water-draw and water use, much more effort has focused on controlling the concentration of radioactive substances in wastewater discharge. In the USA, NRC (1998) required that wastewater discharge of nuclear power plants should comply with the requirements of the *Clean Water Act* as well as the regulations issued by the United States Environmental Protection Agency, NRC and local governments. NRC (2011a) developed a liquid effluent release standard which included three levels of dose limits to individual members (i.e. 3, 25 and 100 mrem per year). According to *Nuclear Safety and Control Act (S.C. 1997, c. 9)* issued in Canada, the Canadian Nuclear Safety Commission may conduct a series of measures if there is contamination in excess of the prescribed limit by a radioactive nuclear substance at any place (Canadian Nuclear Safety Commission 1997). Similar requirements were also developed in France (Nuclear Safety Authority of France 2006) and China (MEP, General Administration of Quality Supervision Inspection and Quarantine of the PRC 2011a, 2011b). In the meantime, wastewater discharge control in successive dry seasons and water conservation in emergency conditions were also improved by countries (Nuclear Safety Authority of France 2006) and international agencies (IAEA 1986a, 1986b, 1994). However, such water resources impact assessment of nuclear power plants were mainly included in environmental impact assessment (EIA) (Department of Justice Canada 2012) or radioactive effluent release assessment (NRC 2011b) which may reveal comprehensive and significant adverse environmental effects caused by a designated project (Department of Justice Canada 2012). Adverse effects impact not only on the aquatic environment, but also the atmospheric, acoustic and ecological environments, and so on. Moreover, as for the aquatic environment, radioactive concentration control of wastewater discharge was emphasized in the impact assessment for other environments. However, water-draw and water use were ignored. In fact, for countries with dense populations and various water users, special WRA should be undertaken for nuclear power plants, especially for those situated inland, considering serious conflicts between water supply and demand as well as many people using surface water as a drinking water source (Shen 2010; Liu *et al.* 2013). China is one such country and has limited water environmental carrying capacity for most inland water bodies (Qu & Fan 2010). Therefore, WRA is required by law and is regarded as a professional method to mitigate the effects of nuclear power industry development on water resources. However, such assessment and management system have not yet been fully established in China. It is especially important for inland nuclear power plants projects considering that they have more negative effects on inland water resources (Butkauskas *et al.* 2012). The objectives of this research are to propose a management system for WRA of nuclear power plants in China which includes the contents, procedures and methods, and present a case study and some suggestions on improving the system in the future.

CONTENTS OF WATER RESOURCES ASSESSMENT FOR NUCLEAR POWER PLANTS IN CHINA

Considering water utilization, WRA for nuclear power plants should particularly concern three aspects (Ding *et al.* 2013). Firstly, operation of a nuclear power plant consumes a large volume of water (Genk & Mohamed 2008), which further intensifies competition for limited water resources. Secondly, a nuclear power plant discharges cooling water and radioactive wastewater, which has a great influence on regional water quality (Abbaspour *et al.* 2012). Thirdly, under accidental conditions, a huge volume of middle or high-level radioactive wastewater may directly discharge into nearby water bodies and cause a series of disasters (IAEA 2011).

According to *Guidelines of Water Resources Assessment for Construction Projects (Trial) (SL/Z322-2005)* (Ministry of Water Resources of the PRC (MWR) 2005) and the characteristics of nuclear power plants in China, it is proposed that WRA for the plants should include the following (Table 1): analysis of the status and development of regional water resources, rationality analysis of water-draw and utilization, water sources assessment, impact analysis of water-draw and wastewater discharge, as well as water resources safety evaluation under accident conditions and the emergency measures required. As for rationality analysis of water-draw and utilization is concerned, suggested values of major water use indicators are shown in Table 2.

PROCEDURES FOR WATER RESOURCES ASSESSMENT FOR NUCLEAR POWER PLANTS IN CHINA

The procedures for a WRA for a nuclear power plant in China should include: (a) site survey and data collection; (b) the assessment agency compiling the work outline of WRA; (c) the related watershed authority approving the outline and making suggestions; (d) the assessment agency modifying the work outline and making a work plan; (e) analyzing the current condition and development of water resources in the site area, evaluating the rationality of water-draw and utilization based on the schemes proposed by the construction unit, and assessing the reliability and feasibility of water sources (i.e. surface water); (f) impact analysis of water-draw and wastewater discharge; (g) completing the first draft of the WRA report, consulting experts and presenting the modified report to the watershed authority; (h) the watershed authority giving preliminary approval to the modified report, providing comments and submitting it to MWR; (i) MWR carrying out technological review and administrative approval; (j) producing the final WRA report (if the application is approved), or re-applying for approval after modifying inappropriate water-related designs (if the application is rejected). Figure 1 shows the proposed procedures of WRA for nuclear power plants in China. Figure 2 shows the feasible procedures of impact analysis of water-draw and wastewater discharge.

METHODS OF WATER RESOURCES ASSESSMENT FOR NUCLEAR POWER PLANTS IN CHINA

Referring to legal documents

WRA for nuclear power plants in China is a legal process to guarantee the security of water resources. So it should follow relevant laws, regulations, specifications, standards, nuclear power industry plans and water resources development plans. The relevant documents includes *Water Law of the PRC* (Order [2002] No. 74) (National People's Congress of the PRC 2002), *Management Approaches of Water Resources Assessment of Construction Projects* (Order [2002] No. 15) (MWR 2002a), *Claim on Enhancing Water Resources Assessment Work of Constructing Projects* (MWR 2002b), *Water Resources Assessment of Construction Projects* and *Guidelines of Water Resources Assessment for Construction Projects (Trial) (SL/Z322-2005)* (MWR 2005), *Integrated Wastewater Discharge Standard (GB 8978-1996)* (MEP, former General Administration of Quality

Table 1 | Contents of WRA for nuclear power plants in China

No.	Item	Content
1	Analysis of the status and development of water resources in the site area	a) for analysis scope: water resources quantity and its time-space distribution characteristics; the quality of water resources; regional nature, society and economy conditions; water resources supply and demand; the situation and potential of water resources development; b) for site area: utilization level of water resources; major problems of water resources development and utilization.
2	Rationality analysis of water-draw and utilization	a) rationality of water-draw: relationship between the project and regional industrial structure, state industrial policy, regional water resources condition, as well as allocation schemes of water resources; impacts of water-draw on regional water resources allocation, other water users, and even regional water utilization structure; b) rationality of water utilization: water use and consumption; the generation and treatment of polluted water and wastewater; water balance and values of water use indicators; pollution reduce measures; adverse impact of water utilization; c) potential of water-saving: the rationality and advancement of water use and water-saving; water use level; water-saving potential; appropriate water-saving measures; reasonable amounts of water-draw and water utilization.
3	Water sources assessment	a) available water quantity of water-draw area and watershed; b) water quality of water-draw area; c) rationality of inlet setting; d) reliability and feasibility of water-draw.
4	Impact analysis of water-draw and wastewater discharge	a) impacts of water-draw; b) impacts of wastewater discharge; c) rationality and feasibility of outlet setting and wastewater discharge schemes; d) water conservation measures; e) mitigation schemes for adverse impacts.
5	Water resources safety evaluation under accident conditions and the emergency measures	a) probability of different grades of nuclear accidents; b) radioactive wastewater discharge schemes under accident conditions; c) impacts of radioactive wastewater discharge on water resources security; d) emergency measures and its applicability and feasibility.

Table 2 | Major water use indicators of WRA for nuclear power plants in China

No.	Indicator	Implication
1	Water-draw amount per 10^4 kWh	Water-draw amount for generating electricity of 10^4 kWh
2	Water consumption amount per 10^4 kWh	Water consumption for generating electricity of 10^4 kWh
3	Cycling rate of indirect cooling water	Percentage of cycling and reuse indirect cooling water of the total indirect cooling water
4	Reuse rate of water resources	Percentage of reuse water of the total water use
5	Reuse rate of steam condensate	Percentage of reuse steam condensate of boiler steam output
6	Growth rate of water utilization	Growth rate of annual water use amount and that of the previous year
7	Compliance rate of wastewater discharge	Percentage of compliance amount of wastewater discharge of the total amount

Supervision Inspection and Quarantine of the PRC 1996), *Environmental Quality Standard for Surface Water* (GB 3838-2002) (MEP, General Administration of Quality Supervision Inspection and Quarantine of the PRC 2002) and *The 12th Five-Year Plan and 2020 Vision of Nuclear Safety and Radioactive Pollution Prevention and Control*.

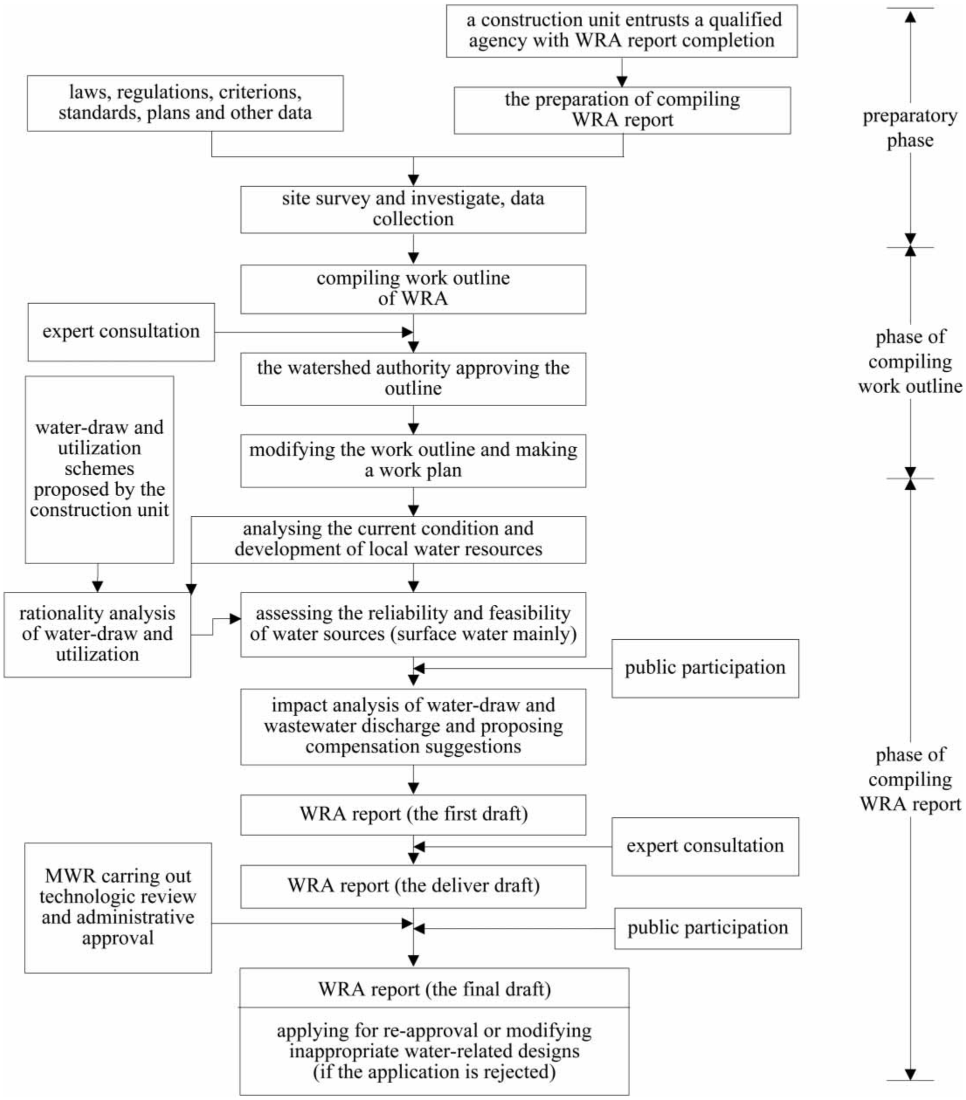

Figure 1 | Procedures of WRA for nuclear power plants in China.

Site surveys

Site surveys are helpful for assessors to understand nature, society and economic characteristics, especially the status of water resources development and utilization, of sites. It is also a useful method to identify regional potential risks and find water-related problems. Assessors may focus on issues related to water consumption and wastewater discharge, such as inlet setting, wastewater treatment facilities, outlet setting, water resource status of water-draw and receiving water bodies, as well as the public's perception and attitudes. In particular, records, photographs, and videos concerning site surveys should be preserved.

Model simulation

In future, China's nuclear power plants, especially inland ones, will adopt AP1000 technology; as this is a new technology, no one has any practical experience of its use. So using data or field monitoring of similar plants is not feasible, and model simulation becomes an important method

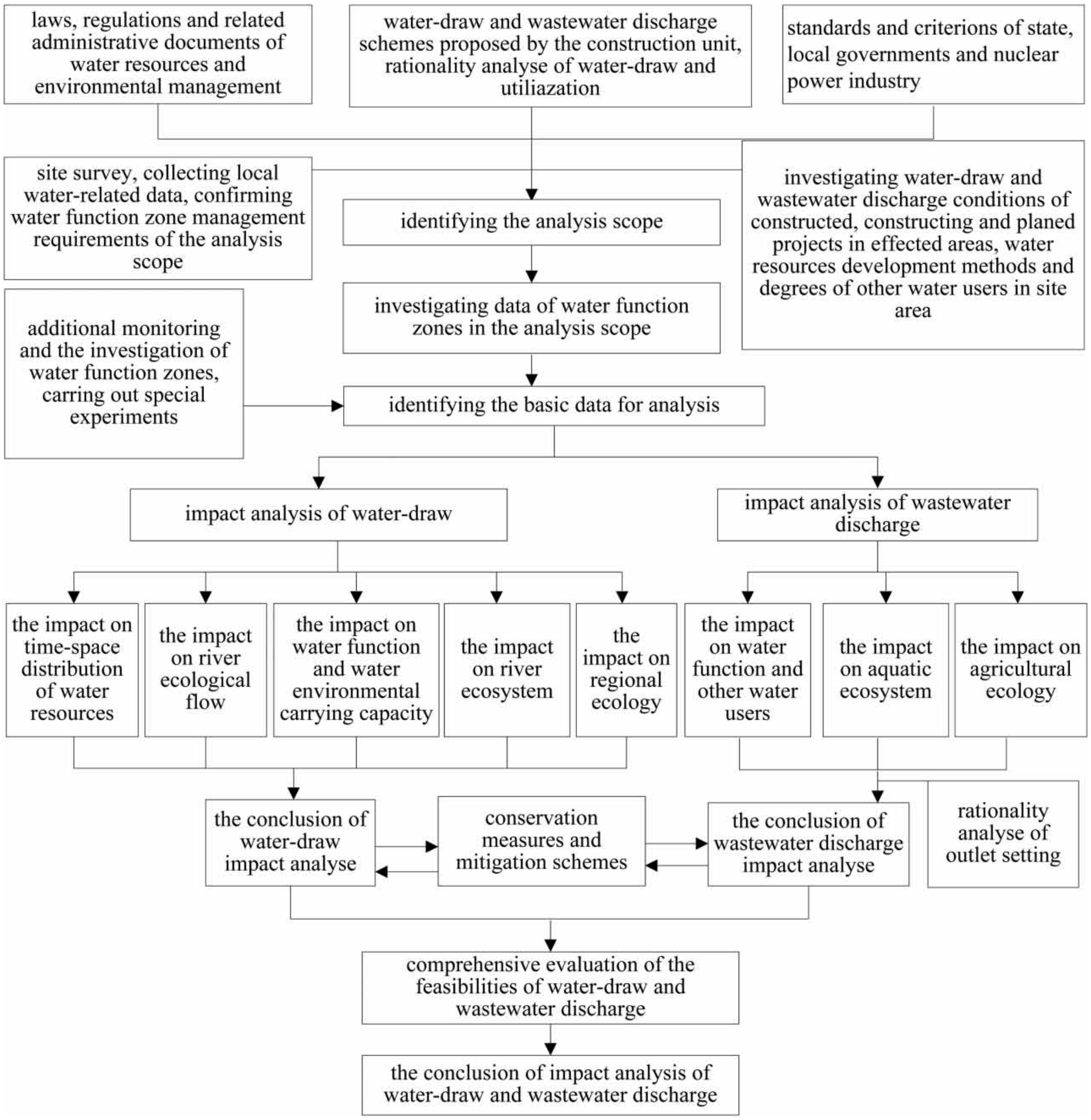

Figure 2 | Process of impact analysis of water-draw and wastewater discharge.

to carry out WRA. The impact of water-draw and wastewater discharge under normal conditions, the impact of wastewater discharge under accident conditions, as well as the effects of emergency measures could be assessed by hydrodynamic (Tsumune *et al.* 2012), water quality (Huang *et al.* 2010) and watershed management models (Laguionie *et al.* 2012). The common models include realizable K-epsilon turbulence model, Joseph's model and the continuous point source model. Suitable software includes FLUENT, MIKE, SMS and so on.

In practical terms, a realizable K-epsilon turbulence model is used to simulate the diffusion and transportation processes of radioactive substances. Joseph's model is an instantaneous point source model, which represents radioactive pollutant concentration accurately in the case of radioactive effluent discharge from an outlet instantaneously. Continuous point source models are a useful tool to reveal radioactive pollution under the condition of continuous radioactive effluent emission. As far as software is concerned, FLUENT is suitable for fluid imitation, MIKE is a professional software for water pollutant numerical simulation, and SMS is appropriate for surface water movement modeling and analyzing.

Expert consultation and public participation

Expert consultation is important for WRA of nuclear power plants in China considering that it is unprecedented, with high technical requirements. It helps assessors to make a more effective work outline, carry out more reasonable evaluation and propose more feasible suggestions. It includes various forms such as report review, discussion and holding colloquia.

In China, surface water is the most important drinking water source and the discrepancy between water demand and supply is prominent; this situation is different from other countries with nuclear power plants. The public pay great attention to nuclear power plants in China. One reason is that water-draw and utilization of the plants would greatly affect other water users of regional watersheds. Another reason is discharge of wastewater (particularly that under accidental conditions) may seriously contaminate drinking water sources. Thus, public participation is necessary and significant for WRA due to its high public sensitivity. Posting notices, releasing information on the internet, door-to-door interviewing, holding hearings and model simulation (Visschers & Siegrist 2013) are adopted. Meanwhile, the accepted opinions or reasons for rejecting should be recorded in WRA reports.

CASE STUDY

Nuclear power plant project description

Hubei Dafan nuclear power plant project was chosen as one of three pioneering inland projects by the Chinese government in 2008. After that year, the site as well as construction unit (China Guangdong Nuclear Power Holding Co. Ltd) were identified and the preliminary works were carried out. The plant, adopting AP1000 technology, will have four units and 5,000 MW total capacity. However, it has been suspended since the Fukushima Dai-ichi nuclear power plant accident happened. According to *The 12th Five-Year Plan and 2020 Vision of Nuclear Safety and Radioactive Pollution Prevention and Control* issued in 2012, it is expected to be constructed during the period of 'the 14th Five-Year' (i.e. 2021 to 2025).

According to the current design, Hubei Dafan nuclear power plant will be located at 29.68°N and 114.68°E in Tongshan county of Hubei province, China, in the vicinity of inland water bodies, i.e. Fushui reservoir (Figure 3). Tongshan county has an area of 2,680 km^2 and a population density of 157.54 people/km^2. Fushui watershed, the local watershed, is a sub-watershed of the middle reach of the Yangtze River basin and covers an area of 5,310 km^2. It has a moist climate, abundance of rainfall, fertile soil and hilly terrain. The volume of water resources in the watershed is 4.28 billion m^3 and its water resources utilization rate is about 9.5%. At present, radionuclide values of Fushui reservoir are at background level and much lower than the limit values. Meanwhile, the water quality meets the state and local surface water environmental standards. Hubei Dafan nuclear power plant project is taken as an example in this research.

Contents of water resources assessment for Dafan nuclear power plant project

The contents of WRA for this project should emphasize water sources, water-draw amount, water use efficiencies, wastewater discharge and hydrodynamic conditions of receiving water bodies, as well as adverse impacts on regional water bodies and other water users.

The designed water source of the project is Fushui reservoir, the multi-annual average runoff of which is 2.22 billion m^3 (Table 3). As for the status quo year, available water quantity is 0.77 billion m^3 and 0.55 billion m^3 with a guaranteed rate of 97% and 99% respectively. As far as a planning year (2020) is concerned, available water quantity can be obtained by predicting total inflow, agricultural water, industrial water, municipal water and ecological water of that year. The result shows the available water quantity will be 0.74 billion m^3 and 0.52 billion m^3 with a guaranteed rate of 97% and 99% respectively in 2020 (People's Government of Xianning City 2006, 2011; China Power Engineering Consulting Group Corporation 2007; Suzhou Nuclear Power Research Institute 2008; Wuhan

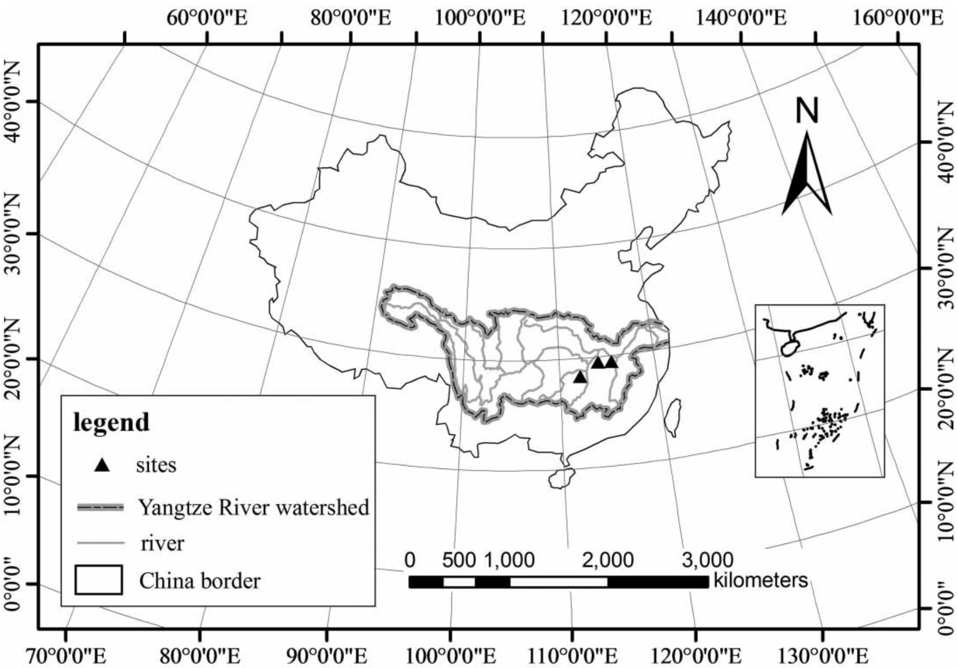

Figure 3 | Location of Hubei Dafan nuclear power plant project in China.

Table 3 | Water utilization indicators of Hubei Dafan nuclear power plant project

No.	Indicator	Design values of Dafan NPP	Values proposed in *Construction Standard of Nuclear Power Plants (Exposure Draft)* (China Power Engineering Consulting Group Corporation 2011)
1	Average runoff of water source (billion m^3)	2.22	–
2	Water-draw amount (m^3/s·GW)	1.25	1.20
3	Water consumption amount (m^3/s·GW)	0.92	1.00
4	Cycling rate of indirect cooling water (%)	98.19	–
5	Reuse rate of water resources (%)	97.59	–
6	Total water use amount (m^3/s·GW)	60.33	–
7	Wastewater discharge amount (m^3/s·GW)	0.35	–
8	Compliance rate of wastewater discharge (%)	100	100

Branch of China Tourism Academy 2011; People's Government of Tongshan county 2013). Similarly, with respect to another planning year (2030), it may reach 0.73 billion m^3 (with a guaranteed rate of 97%) and 0.51 billion m^3 (with a guaranteed rate of 99%) (People's Government of Xianning City 2006; China Power Engineering Consulting Group Corporation 2007; Suzhou Nuclear Power Research Institute 2008; People's Government of Xianning City 2011; People's Government of Tongshan county 2013). Runoff, water level, water quality, water temperature are reliable and the hydrological safety of the site is guaranteed.

The designed water-draw amount is 169.20 million m^3/y, i.e. 6.25 m^3/s and 1.25 m^3/s·GW (Table 3) which meets the demand of *Guide for Water Saving of Thermal Power Plant (DL/T783-2001)* (State Economic & Trade Commission of the PRC 2001) and *Construction Standard of Nuclear Power Plants (Exposure Draft)* (China Power Engineering Consulting Group Corporation 2011). The designed inlet is shoreside and near the Guimuwo area, where the water is deep and the reservoir bank and bottom are stable. The structure for water-draw will be a riverside open channel, whose bottom elevation, bottom width and length will be about 40 m, 30 m and 150 m, respectively.

The plants will adopt indirect cooling water system. The indicators of water consumption amount, reuse rate of water resources, and total water use amount are 0.92 m^3/s·GW, 97.59% and 60.33 m^3/s·GW, respectively (Table 3).

The designed amount of wastewater discharge is 47.67 million m^3/y, i.e. 1.77 m^3/s and 0.35 m^3/s·GW. Most of the discharged wastewater is cooling water, which accounts for 99.98% of the total amount. Cooling water is concentrated wastewater, with salinity higher than that of raw water. It will be discharged into Fushui reservoir if the concentration ratio reaches 3.0 ~ 3.5. It also includes chemical wastewater (2,408.00 m^3/y) and low-level radioactive wastewater (9,974.72 m^3/y) discharged by other systems. Chemical wastewater is generated from demineralized water production, and the condensate polishing, circulating water treatment and chemical injection systems and is mainly released with radioactive wastewater. It can be treated by a pH regulator in a chemical liquid tank or by the Site Radwaste Treatment Facility. Radioactive wastewater, coming from reactor containment and spent fuel pools, is to be conducted by the Liquid Radwaste System and then be stored in a tank for discharge. The wastewater will be discharged into Fushui reservoir, i.e. that water source is also the receiving water body. The inlet of the plant is in the south of the reservoir, while the outlet of wastewater is in the east (29.67°N, 114.70°E). There will be a peninsula between inlet and outlet, so that the outlet will be downstream of the inlet and far away from it. To discharge the cooling water two drainage culverts (diameter 80 cm, length 3,000 m) will be constructed. The drainage culverts will be built along emergency roads at the edge of mountains on the east of the plant and connect to a drainage working well which will be set up near the shore. In this drainage working well, the discharged cooling water and radioactive wastewater will be thoroughly blended and then discharged to Fushui reservoir by a short open channel.

Compared to its multi-annual average runoff (2.22 billion m^3), the designed annual water-draw amount from the Fushui reservoir, 0.17 billion m^3/y and accounting for 7.66% of the total runoff, is relatively small. From the available water quantities with the guaranteed rates of 97 and 99% in different reference years, it is likely that water-draw of the plant can be ensured. Regarding the water level, water quality, water temperature, flood control standard of the Fushui reservoir as well as water-draw amount per 10^4 kWh and that of per million kilowatts capacity of the Hubei Dafan nuclear power plant project, it can be concluded that water-draw requirement can be met under the condition of preserving current water-related functions (domestic water, agricultural water and cultivation water) of Fushui reservoir. Therefore, the designed water-draw scheme is feasible.

The AP1000, designed by Westinghouse (USA), is a third-generation reactor with the most advanced technological level in the world. The designed reuse rate of water resources of the plant will be 95%, which can meet the requirement applying to condensing power plants adopting circulating water supply system. On the basis of water consumption amount, cycling rate of indirect cooling water, reuse rate of water resources and total water use amount, it can be obtained that the designed water use scheme is reasonable.

Using the PWR-GALE program and based on AP1000 design values, annual emission of radioactive nuclide from a single unit can be determined, and the different radioactive materials issued from the whole plant (four units) might be obtained. The tritium discharged to Fushui reservoir would be 1.49×10^{14} Bq/y, and that of other radioactive substances might be 3.78×10^{10} Bq/y. The average discharge concentration of tritium and other radioactive substances will be 3.13×10^3 Bq/L and 0.79 Bq/L, respectively. This indicates that pollutant concentration, especially of radioactive material, could meet the guidelines and requirements. The analysis results revealed that radioactive effects on fish in Fushui reservoir, drinking water sources in lower reaches (indicated by the concentration of total β radioactivity) and the maximum annual effective dose for a person will be acceptable.

The conclusions of the WRA for this nuclear power plant are as following. The water-draw, water use and wastewater discharge are acceptable for regional water resources sustainable utilization and security. Moreover, the design of the inlet and outlet is reasonable.

The proposed suggestions include optimizing the cooling rate and concentration ratio of cooling towers, improving the indirect cooling water system design, reducing the indirect cooling water amount, enhancing the regulation capability of discharge liquid storage tank for different water periods, and strengthening the dispatching management and dam safety monitoring of Fushui reservoir.

Procedures for Water Resources Assessment for Dafan nuclear power plant project

The WRA procedures for Hubei Dafan nuclear power plant project included the followings steps. To begin with, the assessment agency carried out site survey and data collection. Then, the assessment agency compiled the work outline of WRA. In the next phase, Changjiang Water Resources Commission approved the outline. After that, the assessment agency modified the work outline and developed the assessment. In the next stage, the assessment agency carried out expert consultation and presented the WRA report to Changjiang Water Resources Commission. Nowadays, the WRA report has been preliminarily approved by Changjiang Water Resources Commission and submitted to MWR for finally administrative approval.

Methods of Water Resources Assessment for Dafan nuclear power plant project

Methods of WRA for Hubei Dafan nuclear power plant project included referring legal documents, site survey, model simulation, expert consultation and public participation.

Firstly, the assessment agency followed twenty-two laws, regulations, standards, and plans, such as *Water Law of the PRC* (Order [2002] No. 74) (National People's Congress of the PRC 2002), *Management Approaches of Water Resources Assessment of Construction Projects* (Order [2002] No. 15) (MWR 2002a), *Water Resources Assessment of Construction Projects* and *Guidelines of Water Resources Assessment for Construction Projects (Trial) (SL/Z322-2005)* (MWR 2005), *Environmental Quality Standard for Surface Water* (GB 3838-2002) (MEP, General Administration of Quality Supervision Inspection and Quarantine of the PRC 2002), *Water Function Zoning of Hubei Province* (Order [2003] No.101 of Government of Hubei Province) (Hubei Provincial Department of Water Resources 2003) and so on. The assessment also referred to 17 design files, including *Feasibility Research Report of Hubei Dafan Nuclear Power Plant* (China Power Engineering Consulting Group Corporation 2007), *Environmental Impact Report of Hubei Dafan Nuclear Power Plant (Siting Phase)* (Suzhou Nuclear Power Research Institute 2008), and *Capacity Calculating Report of Fushui Reservoir* (Hydrology Bureau of Changjiang Water Resources Commission 2004), etc. Moreover, it was based on 10 approval documents for carrying out preliminary works of the plant construction.

Secondly, site survey was developed to obtain the statuses of site area (such as society, economy, geography, meteorology, geology, river system, hydrology, sediment, terrestrial ecology, aquatic ecology, background value of radioactive level and water quality), regional water resources development and utilization (including water resources quantity and its space-time distribution, water use survey and demand analysis of site watershed, water balance analysis for water users in lower reaches, water users of Fushui reservoir area, ratio of regional water resources development and utilization and so on) as well as potential water-related problems.

Thirdly, several models and software were adopted during the assessment phase. Lake (reservoir) homogenous mixing model was used to calculate the effects of water-draw on pollutant carrying capacity of Fushui reservoir. A reservoir model was utilized to reveal the contribution of radioactive effluent emission to radioactive concentration of Fushui reservoir. And three-dimensional hexahedron and pentahedron computational grid was advanced to simulate the transport and transformation process of radioactive effluent discharged by the plant in Fushui reservoir.

In addition, on 20 April 2006, an experts' consulting conference was held in Wuhan (provincial capital of Hubei), and *Work Outline of Water Resources Assessment Report for Hubei Dafan Nuclear Power Plant* and *Work Outline of Quality Assurance for Water Resources Assessment Report* were evaluated. On 10 December 2006, experts involving the fields of nuclear energy, power generation, environmental protection, nuclear safety, water resources management and so on, were invited to Beijing (the capital of China) to discuss the inflow of Fushui reservoir under the most unfavorable working conditions.

Furthermore, public participation was carried out during the period from July 2006 to February 2007. According to the statistics, 783 questionnaires were issued and 775 effective ones were retrieved, which indicated the recovery rate was 98.98%. As far as the respondents were concerned, 244 people lived within the range of 15 km away from the designed site. Most of the respondents, accounting for 58.8 percent, had received higher education. The proportions of people with secondary education and junior secondary one were 19.8 percent and 21.4 percent, respectively. The results showed that the public paid high attention to the construction and operation of this nuclear power plant, especially its impacts on water environment of Fushui reservoir. The public's concerns focused on the implementation of nuclear safety laws and regulations in the whole process, environmental protection measures and the effects, radioactivity monitoring and information disclosure, etc.

PROSPECT FOR WATER RESOURCES ASSESSMENT FOR NUCLEAR POWER PLANTS IN CHINA

Comparison and selection of several optional sites

Nowadays, WRA for a nuclear power plant in China is carried out for a confirmed site. It is difficult for assessors to deny a site for previous huge investment and manpower, even though it is not suitable considering the status quo of water resources. Water resources management departments can merely provide some suggestions and comments on the premise that the site location is the final one. However, in the future, WRA should be involved in planning and siting stages of the plants. The assessment could concern several optional sites. Assessors could compare and select one site (or sites) considering more water-related qualifications, such as the distance between plants and regional water bodies, the minimum runoff (including annual and momentary ones) of water sources, the space between outlets and drinking water sources and so on. In addition, conditions related to water resources can be considered further in preliminary stages.

Impact assessment of radioactive wastewater discharge on water resources

Under normal working conditions, low-level radioactive wastewater is discharged. The impact assessment on water resources involves transport and decay processes of radioactive substances in receiving water bodies, cumulative effects of radioactive substances on aquatic organisms and so on. Such issues are complicated and interdisciplinary (including hydrology, radiology, biology, and so on), which might be further studied by the support of MWR and related watershed authorities. Moreover, under accident conditions, medium or high-level radioactive wastewater may be discharged into nearby water bodies. The scope, duration and degree of the effect should be assessed quantitatively. So appropriate models, monitoring methods and even simulation softwares are expected to be proposed in the near future.

Public participation

For nuclear power plants in China, most of the receiving water bodies are with drinking water sources downstream. The discharge of radioactive wastewater which has various adverse impacts on water quality and aquatic ecosystem may probably arouse great public concern. Public participation is an effective way to resolve possible water disputes, improve the effectiveness of WRA decision-making, and reflect the democracy of WRA. The degree of public participation should be enhanced during the entire process of WRA. In the future, the impacts of water-draw, water use and wastewater discharge on regional water resources should be disclosed by various channels in time. Public prediction model might be used to reflect the sensitivity of public concerns, and the forms and approaches for WRA will be also specified and unified.

CONCLUSIONS

Nuclear power utilization is important to deal with climate change and energy shortage. In the near future, plenty of nuclear power plants, especially inland ones, will be operated in China, which poses great challenges to China's water resources management. Water resources assessment is a critical method to evaluate the rationalities of water-draw, water use as well as wastewater discharge of such plants. The contents of water resources assessment for a nuclear power plant in China are suggested to include analysis of the status and development of water resources in the site area, rationality analysis of water-draw and utilization, water sources assessment, impact analysis of water-draw and wastewater discharge as well as water resources safety evaluation under accident conditions and the emergency measures. The proposed key processes of water resources assessment are site survey and data collection, compiling a work outline and making a work plan, analyzing the current condition and development of regional water resources, rationality analysis of water-draw and utilization, assessing the reliability and feasibility of water sources, impact analysis of water-draw and wastewater discharge, completing the first draft of the report and modifying, Ministry of Water Resources of the PRC carrying out technological review and administrative approval, accomplishing final report, applying for re-approval or modifying inappropriate water-related designs. Methods of water resources assessment for nuclear power plants may contain referring legal documents, site survey, model simulation, expert consultation and public participation. In the future, water resources assessment for nuclear power plants in China should be improved in the aspects of comparison and selection of several optional sites, impact assessment of radioactive wastewater discharge on water resources, public participation and so on. It is expected that the assessment will be more effective and become a powerful management tool to support sustainable utilization of water resources and security development of nuclear power industry in China.

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