Emergency operation rules for water-supply reservoirs under uncertainty and risk in dry seasons

Bojun Liu, Hao Wang, Xiaohui Lei, Zhengsheng Liu and Jin Quan

ABSTRACT

A better understanding of the forecast uncertainties and risks resulting from potential droughts and sudden water pollution is important in reservoir operations. In this study, we formulated water supply uncertainties and then evaluated risks related to droughts and sudden water pollution. A case study was then performed with the Danjiangkou Reservoir and emergency operation rules were proposed for water supply in dry seasons through the trial and error method. The results show that the reservoir inflow and water pollution location have a significant effect on emergency operations for water supply. However, insufficient reservoir inflow can make the situation worse, resulting in a reduction or even cessation of water supply and consequently enormous economic losses. The water supply problem could be alleviated to some extent with the increase of distance between the pollution location and the reservoir release gate. The proposed emergency operation rules considering forecast uncertainties and risks resulting from potential droughts and sudden water pollution may provide important insights into reservoir water supply in dry seasons.

Key words | Danjiangkou Reservoir, dry season, emergency operation, uncertainty and risk, water supply

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NOMENCLATURE

As	Arsenic
COD_{Mn}	Permanganate index
Cr	Chromium
DJKR	Danjiangkou Reservoir
DSIR	Drought State Index for Reservoirs
EAR	Emergency allowable release
NSC	National standard concentration
NH_3-N	Ammonia nitrogen
Pb	Lead (Pb)
PC	Pollutant concentration
RRV	Restricted release volume
SDC	Synthetic decay coefficient
SNWTP	South–North Water Transfer Project
SWR	Safety water resources
TN	Total nitrogen
TP	Total phosphorus
UQV	Uncertainty-quantified value
WD	Water demand
WS	Water supply
WSSD	Water supply-safety difference
WSL	Water supply loss

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INTRODUCTION

Water resources have become so depleted in recent years that they are unable to meet the ever-increasing demands from the industrial, domestic, agricultural and eco-environmental sectors (Falkenmark 1995; Wu 1999; Chen *et al.* 2016). A solution to this problem is the optimization of reservoir operation, which makes it possible to maximize the utilization of limited water resources (Wu & Chen 2012, 2013). Drought occurs when the water supply is insufficient to satisfy the demands from various sectors (Wilhite & Glantz 1985; Huang & Chou 2008). However, it is noted that drought can be a relatively slow process, and sometimes the change is so subtle that it is not readily detected in a short time (Boix *et al.* 2010; Dabrowski *et al.* 2014; Yan *et al.* 2014). There have been surprisingly few studies on reservoir operations under drought conditions (Folland *et al.* 1986; Keyantash & Dracup 2004; Gil *et al.* 2011; Haro *et al.* 2014; Van Loon & Laaha 2015), and a systematic operation system consisting of the forecasting, scheduling, and mitigation of drought is currently unavailable (Huang & Yuan 2004).

Sudden water pollution accidents in a reservoir would cause deterioration of water quality, thus resulting in a reduction or even cessation of water supply (Cai & Hu 2006; Jiang *et al.* 2010; Zhao et al. 2013; Ma *et al.* 2014). Insufficient inflow under drought can significantly degrade water quality, thus also resulting in a further depletion of available water resources (Kagalou *et al.* 2008; Kuo *et al.* 2008; UNEP 2010). An effective reservoir operation is expected to be able to cope with drought and sudden water pollution accidents (Booker *et al.* 2005; Hu *et al.* 2014; Shokri *et al.* 2014; Wanders & Wada 2015; Zhang *et al.* 2015). However, the uncertainty induced by population growth, increasing water demand, limited management models, sudden water pollution accidents and possible drought events makes it difficult for reservoir operations to achieve the optimum performance (Jia *et al.* 2006; You & Yu 2013; Ghimire & Reddy 2014; Haddad et al. 2014; Liu *et al.* 2014a, 2014b; Zhao & Zhao 2014a, 2014b). This effect appears to be more pronounced in dry seasons than in flood seasons. Despite considerable progress in understanding the uncertainty of reservoir operations in recent years (Azevedo *et al.* 2000; Kerachian & Karamouz 2006, 2007; Kuo *et al.* 2007; You & Cai 2008; Kasprzyk *et al.* 2009; Mishra & Singh 2009; Li *et al.* 2010; Shen *et al.* 2013; Wright *et al.* 2014), there have been few studies on the emergency operations of a reservoir dedicated to water supply considering both drought and sudden water pollution. Clearly, knowledge of how to quantify uncertainty and its potential impacts is required to obtain effective emergency reservoir operations for water supply.

In this study, we analyzed the uncertainty related to inflow, drought and water pollution of water-supply reservoirs, based on which emergency operation models were proposed to solve the water supply problem in dry seasons. In this paper we describe the formulation of water supply uncertainty, methods used to evaluate water supply risks including drought and water pollution, and implications of water supply uncertainty. This is followed by a case study of the Danjiangkou Reservoir, and the proposed emergency operation rules.

EVALUATION METHOD AND FORMULATION

Drought risk evaluation method

Droughts can be classified into five major categories: (1) meteorological drought caused by reduction in precipitation; (2) hydrological drought caused by changes in streamflow; (3) agricultural drought caused by insufficient soil moisture; (4) ecological drought caused by ecological water deficiency; and (5) socioeconomic drought caused by water shortage (AMS 1997; Wilhite 2005; Mishra & Singh 2010). Generally, the reservoir drought belongs to the category of hydrological drought caused by insufficient inflow (Boix *et al.* 2010; Yan *et al.* 2013, 2014; Dabrowski *et al.* 2014). In this study, an effective diagnostic method called the Drought State Index for Reservoirs (DSIR) (Haro *et al.* 2014) is used to assess reservoir droughts.

$$\text{If } V_n \geq V_{av}\text{, then DSIR} = \frac{1}{2}\left[1 + \frac{V_n - V_{av}}{V_{\max} - V_{\min}}\right]; \tag{1}$$

$$\text{If } V_n < V_{av}\text{, then DSIR} = \frac{1}{2} \times \frac{V_n - V_{\min}}{V_{av} - V_{\min}}. \tag{2}$$

where V_{av} is the average of the selected indicator in the data series; V_n is the value of the selected indicator in the operation stage n; $V_{\max}$ and $V_{\min}$ are the maximum and minimum values of the selected indicator in the data series, respectively.

In order to increase the accuracy of DSIR, reservoir storage (S_n), which plays a significant role in ensuring the current and future downstream water supply (Q_n), and reservoir inflow, which can directly determine the current availability of water resources, are selected as reflective indicators (Boehrer et al. 2010; Su *et al.* 2013). Thus, DSIR can be expressed as:

$$\text{DSIR} = 0.6 \times \text{DSIR}_S + 0.4 \times \text{DSIR}_Q \quad (3)$$

where DSIR_S and DSIR_Q are the reservoir storage and reservoir inflow, respectively; and DSIR is the final result. Table 1 shows the drought grades of DSIR.

Water quality risk evaluation method

Water quality is as important as water quantity in satisfying the water demands from various sectors, but it has attracted less attention in terms of investment, technological support and public concern (UNESCO 2012). There is a practical need to investigate the relationship between sudden water pollution and emergency reservoir operations in order to minimize economic losses brought about by poor water quality. Figure 1 shows that a reservoir system can be regarded as a unit water body, in which the water quality at the cross-section before the dam should reach the standard for water supply.

For a unit of water i, according to the source and transport of pollutants in the flow process, the principle of mass conservation and water balance equation (Beck 1987; Hamilton & Schladow 1997; Campbell *et al.* 2001; Xia 2012):

$$\Delta S_i = Q_i + \Delta q_i - ET_i - R_i \quad (4)$$

$$\Delta C_i = \frac{Q_i C_i + W_i + \Delta q_i C_{qi}}{S_i} - \left(\frac{\Delta q_i + \Delta S_i + R_i}{S_i} + K_i \right) C_{i+1} \quad (5)$$

where ΔS_i, Q_i, R_i, ET_i, and Δq_i have the same meaning as that in Figure 1, (m³); S_i is the reservoir storage, m³; C_i, C_{i+1} and C_{qi} are the water quality concentrations of reservoir inflow, reservoir release and local inflow, respectively, mg L^{-1}; K_i is the synthetic decay coefficient (*SDC*) of a given pollutant, d^{-1}; and W_i is the total pollution load of all point sources in the reservoir, ton.

It is supposed that $S_i = a_i R_i$, where a_i is the release and storage coefficient, and then Equation (5) can be re-expressed as:

$$C_{i+1} = \frac{Q_i C_i + W_i + \Delta q_i C_{qi}}{\Delta q_i + \Delta S_i + R_i (1 + a_i K_i)} \quad (6)$$

$$R_i = \frac{Q_i C_i + W_i + \Delta q_i C_{qi} - C_{i+1}(\Delta q_i + \Delta S_i)}{C_{i+1}(1 + a_i K_i)} \quad (7)$$

Assume that a sudden water pollution accident occurs at a certain point in the reservoir. The total point source pollution load (W_i) can be expressed as:

$$W_i = C_{i+1} e^{(L_i K_i / v)} \cdot (Q_i + \Delta q_i) - Q_i C_i \quad (8)$$

$$L_i = \frac{v}{K_i} \ln \left(\frac{W_i + Q_i C_i}{(Q_i + \Delta q_i) C_{i+1}} \right) \quad (9)$$

where L_i is the distance between the pollution point and the delivery port, km; and v is the mean velocity in the reservoir, m s^{-1}. R_i can be considered as the restricted release volume (*RRV*) in the emergency operation for the sudden pollution.

Table 1 | Drought grades of DSIR

Drought grades	DSIR range
Emergency	DSIR < 0.1
Alert	0.1 ≤ DSIR < 0.3
Pre-alert	0.3 ≤ DSIR < 0.5
Normality	DSIR ≥ 0.5

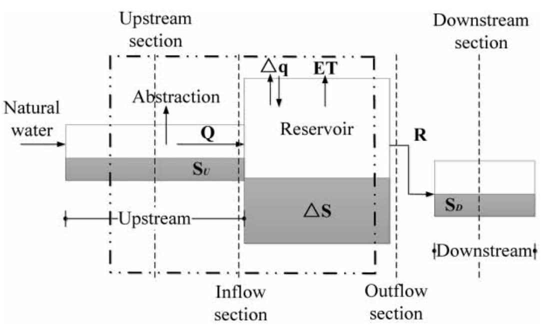

Figure 1 | Generalized structure of a reservoir (where Q and R are the reservoir inflow and reservoir release, $\triangle q$ is the difference between local inflow and water withdrawal, ET is the evapotranspiration, $\triangle S$ is the storage variation; S_U is the initial water volume in the upstream section; and S_D is the initial water volume in the downstream section, respectively).

Water supply uncertainty

Water supply uncertainty

For water-supply reservoirs, the introduction of hydrological, meteorological and social information into inflow and water demand forecast models can result in forecast uncertainty, which can affect operational decisions and can even cause operational risks and economic losses. It is clear that the longer the forecast period is, the higher the uncertainty would be (Montanari & Brath 2004; Zadeh 2005). Forecast uncertainty can be reduced with the use of an hourly updated forecast method. A better understanding of the quantification of forecast uncertainty is important, as this can be used to optimize emergency reservoir operations and thus contribute to mitigate potential losses resulting from forecast uncertainty. Reservoir inflow, reservoir release, net evaporation loss, and other losses in stage t are denoted as $Q_{v,t}$, $R_{v,t}$, $E_{v,t}$ and $L_{v,t}$, respectively. Thus, the water balance equations for a reservoir are (Zhao et al. 2012; Fayaed et al. 2013; Zhao & Zhao 2014a, 2014b; Nunes & Pruski 2015):

$$S_1 = S_0 + Q_{v,1} - R_{v,1} - E_{v,1} - L_{v,1} \tag{10}$$

$$S_2 = S_1 + Q_{v,2} - R_{v,2} - E_{v,2} - L_{v,2} \tag{11}$$

where $t = 1$ and $t = 2$ are the current (Stage 1) and future (Stage 2) stages, S_0 is the initial storage at the beginning of Stage 1, S_2 is the final storage, and S_1 is the carried-over storage from Stage 1 to Stage 2, respectively.

$E_{v,t}$ and $L_{v,t}$ are combined to be $EL_{v,t}$, and eliminating S_1 in both Equations (10) and (11) yields:

$$S_2 = S_0 + Q_{v,1} + Q_{v,2} - R_{v,1} - R_{v,2} - (EL_{v,1} + EL_{v,2}) \tag{12}$$

If we assume that water supply is the primary objective of the reservoir, and all reservoir releases are used to satisfy water demands (including domestic, industrial, agricultural and eco-environmental water), then the reservoir release can be expressed as:

$$R_{v,t} = WD_{v,t} + \chi_{v,t}, \tag{13}$$

where $\chi_{v,t}$ is the difference between water demand $WD_{v,t}$ and reservoir release $R_{v,t}$.

The final storage S_2 shall be a constant, as it is fixed by empirical methods at the beginning of Stage 2 in actual reservoir operation. Thus:

$$\begin{aligned} &WD_{v,1} + \chi_{v,1} + WD_{v,2} + \chi_{v,2} \\ &\quad = S_0 - S_2 + Q_{v,1} + Q_{v,2} - (EL_{v,1} + EL_{v,2}) \end{aligned} \tag{14}$$

In real-time operation, inflow forecast is useful for making operational decisions. However, an accurate inflow forecast can be difficult, if not impossible, to make due to the limitation of projection technology. Besides, forecast uncertainty can also arise from the errors of actual inflow values. Thus, $Q_{v,t}$ can be expressed as follows:

$$Q_{v,t} = \bar{Q}_{v,t} + \delta_{v,t} \tag{15}$$

where $\bar{Q}_{v,t}$ is the inflow forecast, and $\delta_{v,t}$ is the inflow forecast error.

$(EL_{v,1} + EL_{v,2})$ is expressed as $EL_{v,1+2}$, and then the substitution of Equation (15) into Equation (14) yields:

$$\begin{aligned} &WD_{v,1} + WD_{v,2} = \bar{Q}_{v,1} + \bar{Q}_{v,2} + (\delta_{v,1} - \chi_{v,1} + \delta_{v,2} - \chi_{v,2}) \\ &\quad + (S_0 - S_2) - EL_{v,1+2} \end{aligned} \tag{16}$$

Equation (16) indicates that timely adjustment of water supply operation is required under uncertainty, which can be divided into two cases. (1) If $(\delta_{v,1} - \chi_{v,1} + \delta_{v,2} - \chi_{v,2}) < 0$, and $WD_{v,1} + WD_{v,2} < \bar{Q}_{v,1} + \bar{Q}_{v,2} + (S_0 - S_2) - EL_{v,1+2}$, the inflow is overestimated. The reservoir releases more water and subsequent inflow could not satisfy storage requirement, thus resulting in an increase in future drought risk. (2) If $(\delta_{v,1} - \chi_{v,1} + \delta_{v,2} - \chi_{v,2}) > 0$, and $WD_{v,1} + WD_{v,2} > \bar{Q}_{v,1} + \bar{Q}_{v,2} + (S_0 - S_2) - EL_{v,1+2}$, the inflow is underestimated. Water is impounded and the release may not be able to satisfy water demands, thus resulting in an increase in future water supply risk.

Forecast uncertainty of water demand is also considered in each stage:

$$WD_{v,t} = \overline{WD}_{v,t} + \gamma_{v,t} \tag{17}$$

where $t = 1, 2$, $\overline{WD}_{v,t}$ is the water demand forecast and its error is $\gamma_{v,t}$.

Thus, Equation (16) can be re-expressed as:

$$\overline{WD}_{v,1} - \bar{Q}_{v,1} + \overline{WD}_{v,2} - \bar{Q}_{v,2} = (\mu_{v,1} - \gamma_{v,1} - \chi_{v,1} + \mu_{v,2} - \gamma_{v,2} - \chi_{v,2}) + (S_0 - S_2) - EL_{v,1+2} \quad (18)$$

In Equation (18), $[\overline{WD}_{v,1} - \bar{Q}_{v,1} + \overline{WD}_{v,2} - \bar{Q}_{v,2} + EL_{v,1+2} - (S_0 - S_2)]$ is the uncertainty-quantified value (UQV).

Water supply loss under uncertainty

In dry seasons, reservoir operators would rather incur a sequence of smaller shortages in water supply than one potential catastrophic shortage due to decision failure induced by forecast uncertainty during reservoir operation (Lund & Reed 1995; Zhao et al. 2011; Wang & Liu 2013). Suppose that Stage 1 has only one operation stage and Stage 2 has $(N-1)$ operation stages, $R_{v,mar}$ is the maximum allowable release of a reservoir in each stage and $OW_{v,t}$ is the water resources from groundwater, diverted water, unconventional water (e.g., reclaimed, saline, rain and sea water). Thus, when

$$WD_{v,1} > R_{v,1,mar} + OW_{v,1} \text{ and } WD_{v,2} > \sum_{k=2}^{N} R_{v,2,k,mar} + OW_{v,2}$$

or

$$\gamma_{v,1} > R_{v,1,mar} + OW_{v,1} - \overline{WD}_{v,1} \text{ and } \gamma_{v,2} > \sum_{k=2}^{N} (R_{v,2,k,mar}) + OW_{v,2} - \overline{WD}_{v,2}$$

water demands are not satisfied. $(R_{mar} + OW_v - \overline{WD}_v)$ is defined as the water supply-safety difference ($WSSD$). Assuming that forecast errors $\gamma_{v,1}$ and $\gamma_{v,2}$ follow the Gaussian distribution ($\gamma_{v,t} \sim N(0, \sigma_{v,t}^2)$) (Maurer & Lettenmaier 2004), thus, $f(\gamma_{v,t}) = \frac{1}{\sqrt{2\pi}\sigma_{v,t}} \exp\left(-\frac{\gamma_{v,t}^2}{2\sigma_{v,t}^2}\right)$ (Valeriano et al. 2010; Zhao et al. 2014). Here, k is the stage number in Stage 2 ($2 \le k \le N$), and $\sigma_{v,1}$ and $\sigma_{v,2}$ are the forecast uncertainty of water demands in Stage 1 and 2, respectively. The $WSSD$ in each stage is:

$$WSSD_1 = R_{v,1,mar} + OW_{v,1} - \overline{WD}_{v,1} \quad (19)$$

$$WSSD_{2,k} = R_{v,2,k,mar} + OW_{v,2,k} - \overline{WD}_{v,2,k} \quad (20)$$

$$WSSD_2 = \sum_{k=2}^{N} [R_{v,2,k,mar} + OW_{v,2,k} - \overline{WD}_{v,2,k}] \quad (21)$$

The expectation function of water supply loss (WSL) in Stage 1 is:

$$WSL_1 = \int_{WSSD_1}^{+\infty} f_1(\gamma_{v,1}) d_{\gamma_{v,1}} \quad (22)$$

And the respective and joint expectation functions of WSL in Stage 2 are:

$$WSL_{2,k} = \int_{WSSD_{2,k}}^{+\infty} f_2(\gamma_{v,2}) d_{\gamma_{v,2}} \quad (23)$$

$$WSL_2 = \sum_{k=2}^{N} \left[\int_{WSSD_2}^{+\infty} f_2(\gamma_{v,2}) d_{\gamma_{v,2}} \right] \quad (24)$$

where $f_1(\gamma_{v,1})$ and $f_2(\gamma_{v,2})$ are the probability density functions at $\gamma_{v,1}$ and $\gamma_{v,2}$, respectively. Equations (22)–(24) are the integral functions concerning WSL and $WSSD$, and the $WSSD$ values (marginal contribution of WSL) can be calculated as follows (elaborated in the Supplementary Information, available with the online version of this paper):

$$WSL'(WSSD_1) = -\frac{1}{\sigma_{v,1}\sqrt{2\pi}} \exp\left(-\frac{WSSD_1^2}{2\sigma_{v,1}^2}\right)' \quad (25)$$

$$WSL'_{2,k}(WSSD_{2,k}) = -\frac{1}{\sigma_{v,2}\sqrt{2\pi}} \exp\left(-\frac{WSSD_{2,k}^2}{2\sigma_{v,2}^2}\right) \quad (26)$$

$$WSL'_2(WSSD_2) = -\sum_{k=2}^{N} \left[\frac{1}{\sigma_{v,2}\sqrt{2\pi}} \exp\left(-\frac{WSSD_2^2}{2\sigma_{v,2}^2}\right)\right] \quad (27)$$

Meanwhile, the second-order derivatives of WSL_1 and WSL_2 are:

$$WSL_1''(WSSD_1) = \frac{WSSD_1}{\sigma_{v,1}^3\sqrt{2\pi}}\exp\left(-\frac{WSSD_1^2}{2\sigma_{v,1}^2}\right) \tag{28}$$

$$WSL_{2,k}''(WSSD_{2,k}) = \frac{WSSD_{2,k}}{\sigma_{v,2}^3\sqrt{2\pi}}\exp\left(-\frac{WSSD_{2,k}^2}{2\sigma_{v,2}^2}\right) \tag{29}$$

$$WSL_2''(WSSD_2) = \sum_{k=2}^{N}\left[\frac{WSSD_2}{\sigma_{v,2}^3\sqrt{2\pi}}\exp\left(-\frac{WSSD_2^2}{2\sigma_{v,2}^2}\right)\right] \tag{30}$$

Implications for water supply operation

In Equations (25)–(27), WSL_1', $WSL_{2,k}'$ and WSL_2' (marginal loss of water supply) are all negative when water demands are not satisfied, indicating that they are diminishing functions with respect to $WSSD_1$, $WSSD_{2,k}$ and $WSSD_2$, respectively. Meanwhile, the smaller the water demand forecast is, the lower the WSL under constant $R_{v,mar}$ will be. However, $R_{v,mar}$ is actually variable as reservoir operation needs to be adjusted in order to better characterize dynamic storage, thus resulting in uncertainty in water demand forecast. It follows from Equations (28)–(30) that $WSL_1''(WSSD_1) > 0$, $WSL_{2,k}''(WSSD_{2,k}) > 0$ and $WSL_2''(WSSD_2) > 0$, indicating that WSL_t ($t = 1, 2$) are the convex functions of $WSSD_j$ ($j = 1, 2$). Figure 2 shows that

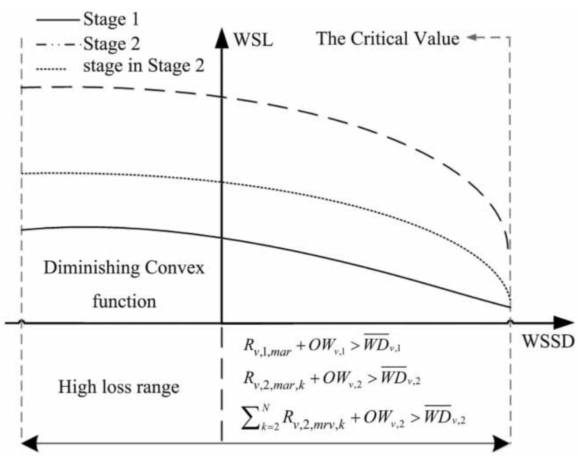

Figure 2 | Linear relationship curves between *WSL* and *WSSD*.

WSL would become smaller with the increase of *WSSD*. When water supply is insufficient to meet water demand, the higher the release capacity of a water supply reservoir is, the smaller the *WSL* will be, which implies that *WSSD* has an effect on the decreasing marginal utility of *WSL*. Accordingly, two operation rules can be suggested for water supply: (1) it would be better to reduce *WSL* in dry seasons to store more water in one or two large reservoirs rather than in several reservoirs of different sizes; and (2) it would be difficult for reservoir operations to maximize the comprehensive benefits unless the water storage in the large reservoir is increased, and water supply and power generation are the major objectives of the reservoir in dry seasons. In rules (1) and (2), *WSL* is the diminishing function of *WSSD* and a hydrologic drought is happening or about to happen; otherwise, it would be expected to become water stressed and drought intensified according to rule (1) and (2) for the purpose of *WSL* reduction.

Data, criteria and limitation in the calculation

The data needed in the calculation include daily reservoir storage, daily reservoir inflow, daily reservoir release, daily evaporation and other losses, daily local inflow, daily forecasting inflow, daily forecasting water demand, and the total point source pollution load. The daily release and storage coefficient (a in Equation (6)) can be calculated from the ratio between reservoir storage and reservoir release; and the value of *SDC* (K in Equations (6) and (7)) is selected from the research in the study area. If not available, the two-dimensional hydrodynamic and water-quality model needs to be built to calibrate this parameter and then compute its value. In addition, the premise is that the water supply of the reservoir is sufficient to satisfy the water demands from various sectors and the water quality reaches the standard required. Emergency operation rules are appropriate for hydrological conditions with high uncertainty of reservoir inflow and moderate or severe drought in future years (Shiau 2003; Celeste & Billib 2009). It would be better to obtain emergency operation rules for large- and extra large-size reservoirs than for medium- and small-size reservoirs considering their sufficient operation and storage capacity.

CASE STUDY

A case study is conducted with the data from the Danjiangkou Reservoir (DJKR) (32°36′–33°48′N, 110°59′–111°49′E) in dry seasons for the demonstration of the proposed emergency operation rules. DJKR (Figure 3) is located near Danjiangkou City (Hubei Province) and in Xichuan County (Henan Province) in the upper and middle reaches of the Han River, and one of its major purposes is to supply water to the middle and lower reaches of the Han River basin. It is also the water source for the middle route of the South–North Water Transfer Project (SNWTP), which plays a strategic role in the allocation and management of water resources in China. It has an average annual inflow from the Han River and Dan River of 39.48 bn m^3, a water storage capacity of 29.05 bn m^3, a storage water level of 170 m, and a volume of water to be diverted per year of 13 bn m^3. However, a potential threat to water supply is drought and pollutants like COD, NH_3-N, As and Pb, which can be affected by climate changes and human activities (Li et al. 2008, 2009; Liu et al. 2014a, 2014b; Ma et al. 2014; Chen et al. 2015).

The cumulative departure curve based on the cumulative difference between normal and mean values is widely used to evaluate changes of selected factors. The cumulative departure curve of DJKR inflows from 1956 to 2006 is shown in Figure 4. A significant fluctuation in inflow is clearly observed in 1956–1962, 1965–1975, 1985–1989 and 2002–2006, indicating the alternation of wet and dry seasons over a short period of three years. The four-year period

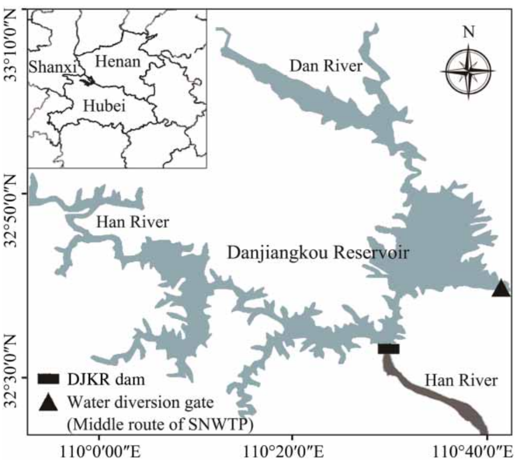

Figure 3 | Location of study area.

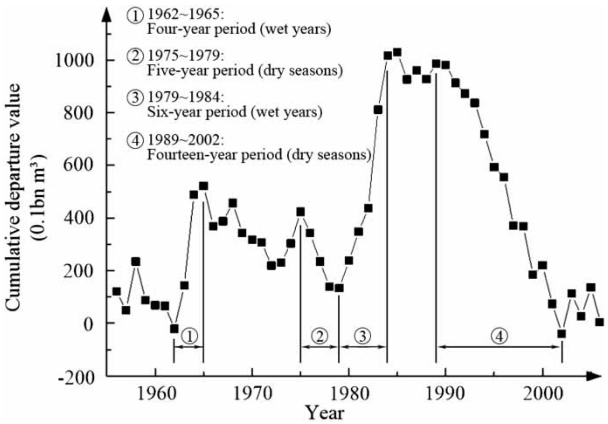

Figure 4 | The cumulative departure curve of annual inflows in DJKR.

1962–1965 and the six-year period 1979–1984 are wet years, whereas the five-year period 1975–1979 and the fourteen-year period 1989–2002 are dry seasons, respectively. Thus, there is low inflow in the period 1990–2006.

The concentration degree (C_d) and period (D) are used to characterize runoff distribution using monthly runoff data in a year. The C_d values range from 0 to 1, and the closer the value is to 1, the more uneven the runoff distribution in a year would be; whereas the closer it is to 0, the more even the runoff distribution in a year would be. Table 2 shows that inter-annual C_d values are statistically significant in a descending trend, and DJKR inflows as a whole are distributed evenly in a year. In addition, DJKR inflows are concentrated in late July during 1956–1959 and 1990–1999, early August during 1970–1979, 1980–1989 and 2000–2006, and mid August during 1960–1969.

Generally, the dry season in DJKR lasts approximately 120 days from November to February in a year (Liu et al. 2013; Wang et al. 2015; Yang et al. 2016), which is divided into 12 stages of 10 days each in this study ($v = 10$).

Table 2 | Concentration degree and period of inflows in DJKR

Years	C_d	D
1956–1959	0.507	184.59°
1960–1969	0.376	207.21°
1970–1979	0.414	200.16°
1980–1989	0.476	204.28°
1990–1999	0.400	185.70°
2000–2006	0.421	199.84°

Accordingly, the reservoir will be operated by stages. The first stage is referred to as the current stage (Stage 1), and the rest as future stages (Stage 2), respectively. Sudden water pollution is assumed to occur after Stage 1, and emergency reservoir operation will be executed in Stage 2. In dry seasons, water impounding should be increased from the fourth dry season to cope with water shortage, but reduced from the subsequent flood season to increase reservoir capacity.

RESULTS AND DISCUSSION

The maximum allowable release of DJKR in each stage is variable depending on the forecast of sudden events, and is expressed as the emergency allowable release, *EAR* 1 in Case 1, in which drought is likely to occur but without sudden pollution, and *EAR* 2 in Case 2, in which drought is likely to occur with sudden pollution. NH_3-N, a typical pollutant in water-supply reservoirs, is selected as the water-quality indicator (Li *et al.* 2009; Ma *et al.* 2014; Tan *et al.* 2014). In DJKR: (1) the initial storage is 65.34×10^6 m³ and the final storage is 62.30×10^6 m³; (2) of the 15×10^6 m³ of water from other sources, 5×10^6 m³ is the safety water resource (*SWR*) used to compensate for the water deficit caused by forecast uncertainty and potential risks, and the *SWR* value is determined based on water supply-demand balance analysis; and the remaining 10×10^6 m³ is used for water supply; (3) the background concentration of NH_3-N (C_i) is 0.235 mg L^{-1} and its standard concentration (C_{i+1}) should be within Grade II (0.5 mg L^{-1}) according to China's Environmental Quality Standard for Surface Water Quality (GB3838-2002); (4) the *SDC* of NH_3-N is about 0.231 d^{-1} in November, 0.124 d^{-1} in December, 0.126 d^{-1} in January and 0.215 d^{-1} in February, respectively (Li *et al.* 2009; He *et al.* 2011; Tang *et al.* 2014; Wang *et al.* 2014; Ai *et al.* 2015); and (5) the total sudden pollution load is set between 10 and 100 ton. The calculated results for Case 1 and Case 2 are shown in Table 3 and Figure 5.

Table 3 shows that in Case 1, the *WSSD* values are small in Stages 9 and 10, and the corresponding *WSL* values are large. However, the *EAR* 1 in each stage can meet the water demands and reservoir final storage without using *SWR* to reduce uncertainty and risk from operation decisions we have made. In Case 2, sudden pollution occurring after Stage 1 restricts water supply in Stage 2, leading to a significant increase of *WSL*. The *EAR* value is 69.93×10^6 and 63.56×10^6 m³ with a total sudden pollution load of 10 and 100 ton in Stage 2, respectively. The sudden pollution makes reservoir operation a complex issue, and *SWR* must be used to supply water and deal with pollution in the reservoir as quickly as possible. Figure 5 shows the difference values of *UQV*. It shows that although sudden pollution can temporarily increase *WSL* in the operation stages, the

Table 3 | Calculated results for Case 1 and Case 2 with a total pollution load of 10 ton

				Drought forecast (Case 1)				Sudden pollution (Case 2)		
Stage	**Stage**	**Water demand forecast (10⁶ m³)**	**Reservoir inflow forecast (10⁶ m³)**	**Grade**	***EAR* 1 (10⁶ m³)**	**Storage (10⁶ m³)**	***WSSD* (10⁶ m³)**	***EAR* 2 (10⁶ m³)**	**Storage (10⁶ m³)**	***WSSD* (10⁶ m³)**
Stage 1	Stage 1	84.88	74.21	0.30	80.56	57.57	5.68	80.56	57.57	5.68
Stage 2	Stage 2	152.55	136.41	0.49	147.80	45.45	5.25	69.63(*RRV*)	123.61	−72.91
	Stage 3	100.45	99.30	0.57	99.30	43.72	8.85	100.45	121.88	10.00
	Stage 4	124.62	100.73	0.16	126.23	9.34	11.61	134.53	87.20	20.00
	Stage 5	143.53	136.01	0.47	140.12	0.57	6.59	143.53	78.02	10.00
	Stage 6	140.95	91.14	0.07	143.34	−45.13	12.39	155.95	12.81	25.00
	Stage 7	85.89	78.95	0.31	85.89	−47.38	10.00	92.67	−1.88	16.78
	Stage 8	105.37	111.25	0.51	99.66	−36.87	4.29	105.38	2.91	10.00
	Stage 9	127.67	133.63	0.57	120.34	−24.18	2.67	127.67	8.27	10.00
	Stage 10	238.08	218.71	0.45	230.12	−41.76	2.04	238.94	−13.72	10.98
	Stage 11	191.13	176.11	0.63	185.30	−52.85	4.17	191.13	−30.64	10.00
	Stage 12	138.28	123.61	0.40	132.89	−62.30	4.61	148.28	−62.30	20.00
	Total	1548.52	1405.85	0.42	1514.99	\	86.11	1508.25	\	68.73

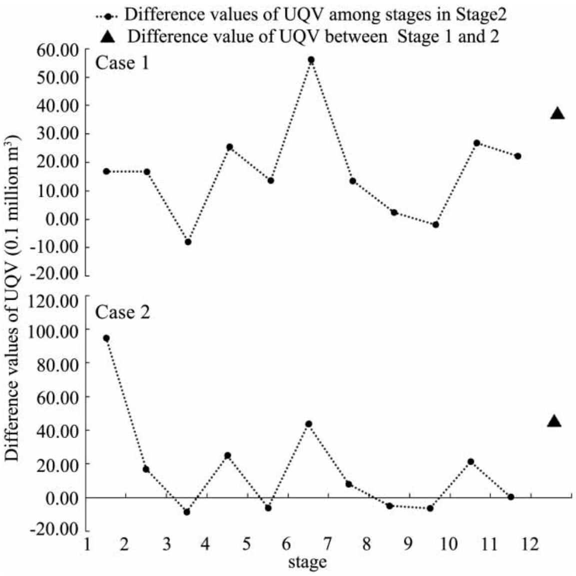

Figure 5 | Difference values of *UQV* during the reservoir operation.

total *WSL* can be reduced with the use of effective release decisions for future water supply. *SWR* plays a key role in reducing the total *WSL* from uncertainty and risk. The difference values of *UQV* in Case 2 show a decreasing tendency, indicating that sudden pollution could remain uncertain to a large degree in each stage of Case 2. Sudden pollution plays a much more important role than drought, and the uncertainty in the operation stages of Case 1 depends on assessment levels of possible droughts, which indicates that the severer the drought peaks are, the higher the *UQV* will be. In dry seasons, as long as *WSSD* is higher than zero, the possibility of water supply failure in the future can be greatly reduced.

Table 4 shows the transport of NH_3-N at the Taocha water diversion gate. It shows that sudden water pollution (NH_3-N with a total load of 100 ton) 6.1 km from the Taocha gate has no significant effect on the water quality at Taocha; whereas pollution occurring within 6.1 km can have a detrimental effect on the water quality at Taocha. In general, the closer the water pollution point is to Taocha, the worse the water quality at Taocha will be. In Case 1, water can be transferred from Taocha as planned and the emergency operation depends on the DJKR dam; whereas in Case 2, the Taocha gate plays a critical role in regulating and controlling the sudden water pollution by decreasing the discharge, because the flow velocity in the majority of the reservoir is almost zero except that near the inlet and outlet. Thus, if the water pollution point is 4.8–6.1 km away from Taocha, water pollution could be completely eliminated by decreasing the release at the Taocha gate (300 $m^3 s^{-1}$) and having a short-term limited outflow of the DJKR dam; if it is 3.6–4.8 km, the release at Taocha is decreased (300 $m^3 s^{-1}$) and the water diversion duration is increased as soon as possible, and then the Taocha gate should be closed once the water quality falls below the standard; if it is within 3.6 km, water diversion through the Taocha gate should be stopped upon the discovery of water pollution, and emergency reservoir operations shall proceed.

Table 4 | Calculated results of NH_3-N transport in Case 2

Pollution point to Taocha (km)	Total load (ton)	Peak concentration at Taocha (mg L^{-1})	Taocha release ($m^3 s^{-1}$)
6.1	100	0.5216	650
	10	0.0074	650
4.8	100	0.5845	350
	10	0.0099	350
3.6	100	0.9597	0–350
	10	0.5656	350
1.8	100	4.8703	0
	10	1.0575	0

The initial reservoir inflow and pollution location are substituted into the equations proposed above, and the objectives are to satisfy domestic and ecological water demands and minimize pollutant concentration ahead of the release gates (Min[$WD_{domestic} + WD_{ecological}$-$WS$], Min[$PC_{ahead\ of\ dam\ gate}$-$NSC$], and Min[$PC_{ahead\ of\ transfer\ gate}$-$NSC$]). Reservoir inflow and pollution location are not modulated by the trial and error method programmed in the MATLAB until the above objectives are achieved. Therefore, emergency operation rules for water supply under uncertainty in dry seasons are deduced and generalized in Figure 6.

CONCLUSIONS

Water-supply reservoirs must first satisfy downstream domestic and ecological water demands in the case of insufficient reservoir inflow, and emergency operation

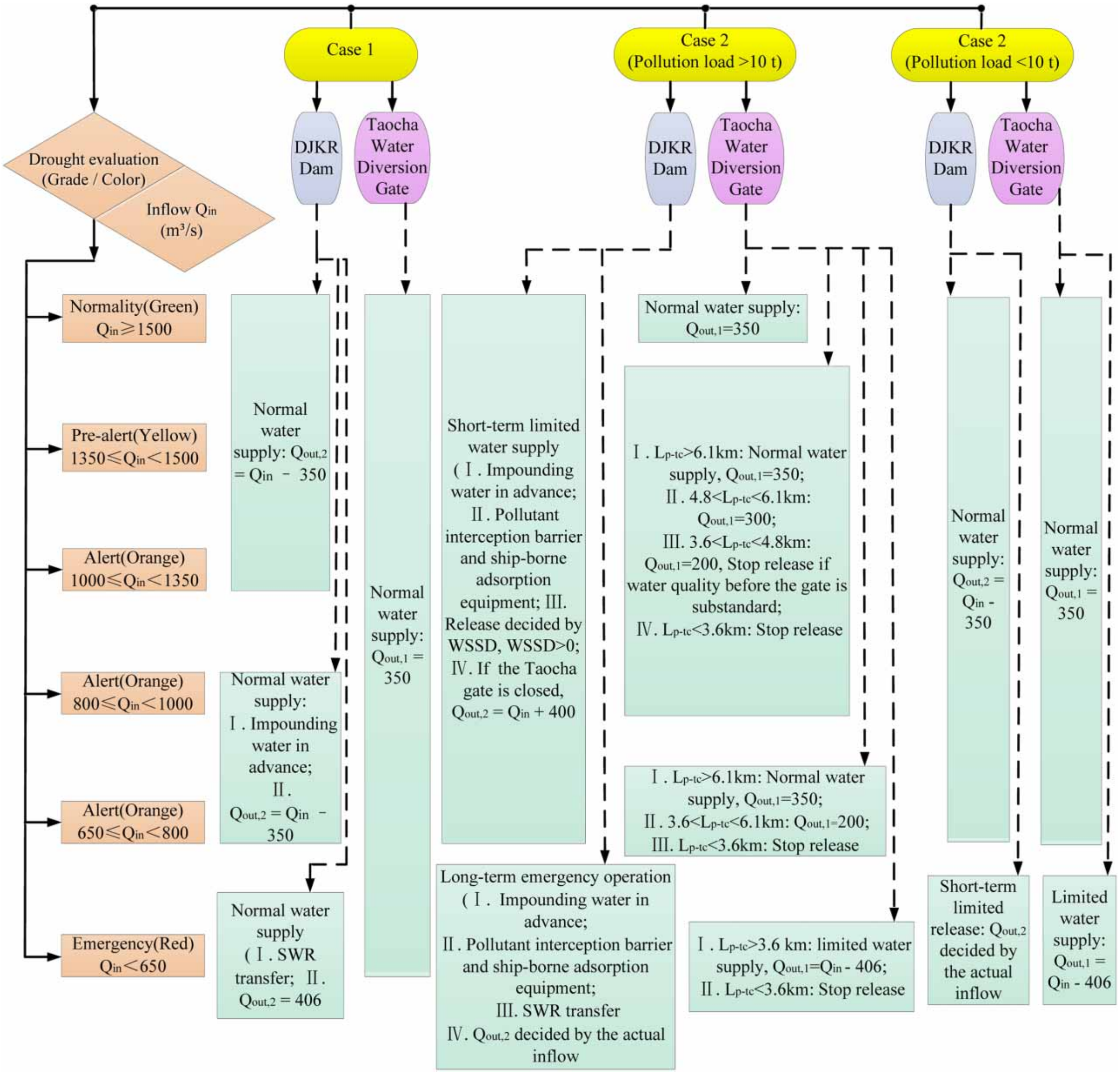

Figure 6 | Generalized emergency operation rules (L_{p-tc} is the distance between the pollution point and the Taocha water diversion gate; Q_{in} is the monthly inflow of DJKR, m³ s^{-1}; $Q_{out,1}$ is the release at the Taocha gate, m³ s^{-1} and $Q_{out,2}$ is the release of DJKR, m³ s^{-1}, respectively).

rules would be unworkable when the reservoir water level is below the lower limit. Reservoir inflow and water pollution location have a significant effect on emergency operation for water supply. However, insufficient reservoir inflow can make the situation worse, resulting in a reduction or even cessation of water supply and consequently enormous economic losses. The water supply problem would be alleviated to some extent with the increase of distance between the pollution location and the reservoir release gate. However, emergency operation will become complex for reservoirs with more than one release gate. For reservoirs with two release gates, water quality can be ensured due to the autoregulation and dilution ability of the reservoir in the case of small-scale water pollution far away from the release gate without using emergency operation. However, emergency operation should be used if reservoir inflow is insufficient, or there is a large quantity of pollutants, or pollution occurs near the release gate. In this case, conventional operation is used at first for each gate to release water, and then the release, turn-off and opening of water diversion gates can be determined on the basis of reservoir inflow and water level. Although water pollution may have a small impact on the water quality when the release is large while water diversion is a continuous low flow, some pollutants may be retained in a certain area of the reservoir and will need to be removed.

Some other conclusions can be drawn from this study: (1) *WSL* is the diminishing function of *WSSD*, indicating that *WSSD* has an effect on the decreasing marginal utility of *WSL*, and thus it can be used as an indicator for operation of water-supply reservoirs; (2) *SWR* can be used for emergency water supply, which plays a key role in reducing the total *WSL* from uncertainty and risk in the case of serious reservoir pollution; (3) drought assessment is helpful to effectively reduce the risks or losses, and improve water supply operations in dry seasons; (4) reservoir operation combined with artificial measures is an effective way to deal with sudden pollution in a reservoir; (5) selecting water supply and power generation as the main objectives of a reservoir in dry seasons could maximize the comprehensive benefits. However, further study is required to better understand the effect of climate change on emergency reservoir operation in dry seasons (Zheng *et al.* 2015; Cortés-Hernández et al. 2016), and to integrate atmospheric, hydrological and water quality models into a single model for emergency reservoir operations in the future.

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