

Research on real-time risk monitoring model along the water transfer project: a case study in China

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ABSTRACT

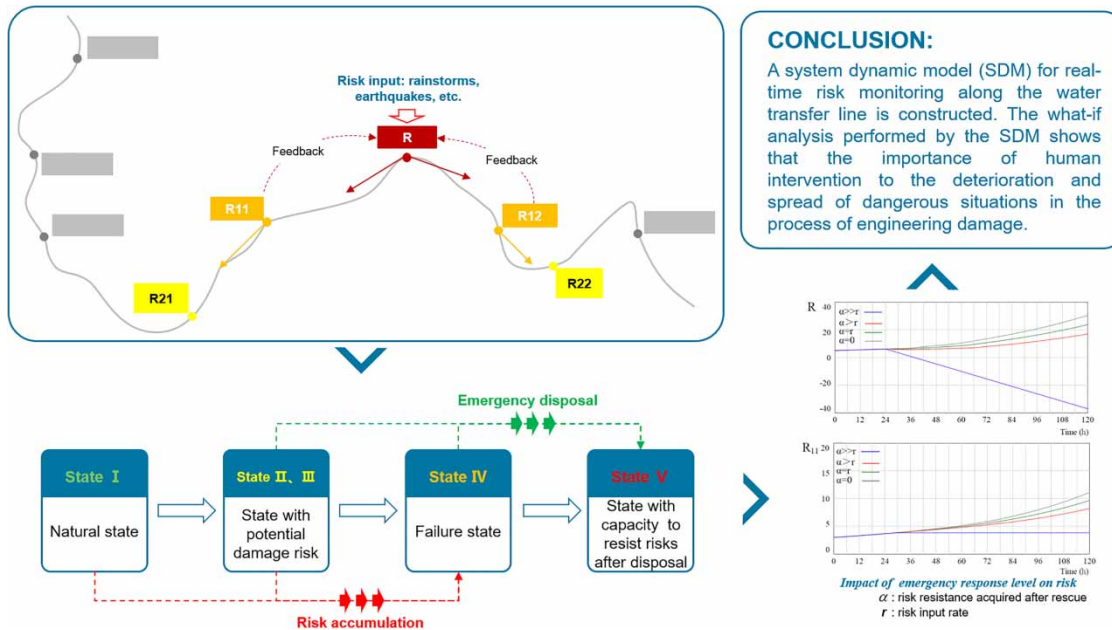
With the continuous operation of a water transfer project, especially under the general trend of global climate change in recent years, extreme weather occurs frequently, and the project's operation process will be tested by natural disasters, structural damage, electromechanical equipment failure, water pollution and other risks. Therefore, the risk management of the water transfer project is of great significance to ensure the long-term operation of the project. As one of the four largest cross-century projects in China, the operation risk of the South-to-North Water Transfer Project has attracted great attention. In this paper, a system dynamic model (SDM) for simulating real-time risk is presented. Based on the linear and directional characteristics of water transfer project and the known risk level of single buildings, DYNAMO language is embedded to connect the risks of various points on the line, and a model for real-time monitoring the risk changes along the line is constructed. The what-if analysis performed by the SDM shows the importance of human intervention to the deterioration and spread of dangerous situations in the process of engineering damage.

Key words: real-time monitoring, risk analysis, simulation, system dynamics

HIGHLIGHT

- In this paper, a system dynamic model (SDM) for simulating real-time risk is presented. Based on the linear and directional characteristics of water transfer project and the known risk level of single buildings, DYNAMO language is embedded to connect the risks of various points on the line, and a model for real-time monitoring the risk changes along the line is constructed.

GRAPHICAL ABSTRACT



1. INTRODUCTION

To solve the problem of extremely uneven distribution of water resources in time and space, compared with green infrastructure, with which it is difficult to meet the needs of rapid economic and social development and modernization, many countries have chosen 'grey' solutions (Muller *et al.* 2015), e.g. water transfer projects, dams, etc.

Although the project's construction will inevitably have a negative impact on the environment, its benefits are also very considerable. The construction and operation of the project also drives the sustainable economic development of the surrounding areas.

Since 1949, the construction of water transfer projects in China has entered a rapid development stage, and the projects generally have the characteristics of large span and long distance. Compared to world-famous water transfer projects, such as the California State Water Transfer Project, the Central Valley Project and the Snowy Mountains Scheme in Australia (Ers-kine *et al.* 1999), the single Chinese MRP (the middle route of the South-to-North Water Transfer Project) had a longer main canal (i.e., 1,277 km long) and many complex hydraulic structures.

The complex geological conditions and changeable operating conditions make dangerous situations occur frequently in flood seasons, even if the government has put in a lot of human and material resources to ensure the safety of the whole life cycle of the project. However, emergency rescue can only recover losses as much as possible. If risk management and control can be carried out while ensuring a certain accuracy, timely intervention and early warning before the arrival of the critical point of damage, then the occurrence of dangerous situations can be completely avoided.

There are generally two views on the object of risk control. One is to regard the project itself as a risk source (Nyssen *et al.* 2018). The other is to regard the project in a stable state as a risk receptor. Driven by various risk factors, the project stability is threatened, which leads to a series of dangerous situations. From the perspective of engineering safety, a water transfer project is obviously studied as a risk receptor. The water transfer project is linearly distributed on the plane, and various structures arranged on the line are points of different sizes. The line refers to the main water transmission canal, and area risk receptors refer to the water source area. Similar to the risk correlation between upstream and downstream reservoirs in the same basin, if the upstream reservoir fails, it will have a great impact on the downstream reservoir (Liu *et al.* 2019). Due to the continuity of water transmission lines in series, the risk can be transmitted along the canal.

This paper concludes the following characteristics associated with traditional dam risk assessment:

1. The risk sources of water transfer project are complex, so it is unrealistic to screen and investigate thoroughly. We should grasp the two focus of risk analysis: one is the key risk receptor and the other is the key risk source (Singh *et al.* 2011). Referring to the risk ranking of dam groups, the key canal sections should be determined according to the risk level, and the engineering safety of high-risk canal sections should be ensured first. For one structure, analyze its main risk sources and give priority to treatment, rather than blindly dealing with all potential risks. Through risk analysis, the project treatment can be more efficient.
2. Due to the long project line, even high-intensity manual inspection cannot ensure that the project is free of hidden dangers. Single-point damage cannot be compared with the serious consequences caused by dam collapse. Therefore, in fact, people have a certain tolerance for engineering defects in water transfer projects (Langdalen *et al.* 2020). In risk assessment, we need to pay attention to the current safety of the project and actively obtain engineering information including manual patrol and monitoring data.
3. King (King *et al.* 2016) investigated a large database of dam safety incidents and drew a similar conclusion that incidents were often complex and not necessarily related to a single extreme event. As a collection of various hydraulic structures, the risk interference of water transfer project is not only a simple accumulation, but also risk transmission between structures, mutual induction and amplification of risks (Putcha & Patev 2000; Leveson 2011; Komey *et al.* 2015). It is necessary to treat the risk of water transfer project from the perspective of system dynamic development (Wang and Yuan 2016).

These characteristics of water transfer projects are different from those of conventional hydraulic structures, resulting in insurmountable difficulties in the risk evaluation and calculation of water transfer projects, e.g. how to grasp the main risks in many structures of water transmission lines; how to simulate the change process of engineering risk; how to evaluate people's tolerance to potential defects on the line. Although these issues are relatively well understood, there is still a lack of targeted strategies to overcome them beyond generic suggestions (e.g. strengthening inspection, risk awareness raising).

Starting from these premises, the present work proposes a system risk simulation model based on system dynamics, for the simulation of a risk transfer process on a water transmission line, with a specific discussion of the impact of emergency response measures on system risk. Specifically, the proposed model aims to: (i) conduct quantitative simulation of internal risk changes of the project; (ii) reveal the process of risk transfer, amplification or stability in the structure group; (iii) discuss the important role of emergency response strength and level in ensuring the long-term operation of the project.

2. FRAMEWORKS AND APPROACHES FOR A WATER TRANSFER PROJECT

2.1. Risk transmission mode of water diversion project

In 2004, the risk element transmission theory was put forward (Li & Liang 2009), which is similar to the engineering risk factor studied in this paper, that is, 'the uncertain factors that affect the specific actual results in a certain environment and within a certain period of time'. However, the risk element does not only refer to a certain risk factor, but also to a collection of multiple risk factors, and the risk element and non-risk element can be transformed into each other. Therefore, if the comprehensive risk level of structures is regarded as a risk element, the theory is also applicable to the analysis of the risk transmission process on the water conveyance line. The transmission mode of risk element includes chain type, layer type, network type, implicit type, chaotic type, etc. But for water transmission lines arranged in series, these transmission methods are not all applicable.

There are two relationships between the two bodies in the system. One is completely independent, and the other is inter-related. Then the two extreme states are that all individuals in the system are independent or interrelated. Obviously, structures on water conveyance line are not completely connected or independent. The canals as one of the risk receptors are also the main link of risk transmission. But whether it will affect the structure adjacent depends on the time, location, degree of failure and human intervention.

Referring to the risk element transmission mode, the basic risk transmission mode on a water conveyance line can be divided into the following three categories (Figure 1):

1. chain type: the risk is one-way uniquely transmitted to the adjacent downstream structures, and the risk transmitted continues to be transmitted to the downstream, forming a chain risk transmission path. This mode is directional, mainly pointing downstream.

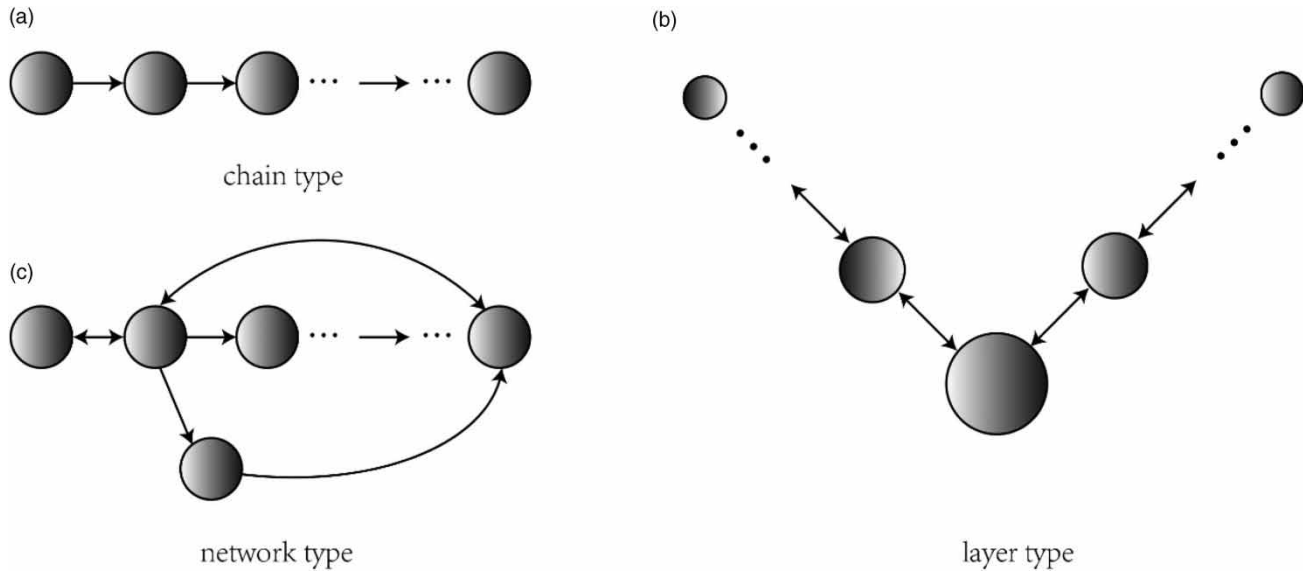


Figure 1 | Three different modes of risk transmission.

2. layer type: the risk is transmitted to adjacent structures on both sides, and centered on that point, the risk continues to be transmitted to adjacent structures. The first damaged structure is the risk top layer, and the structures adjacent to it are the second layer. This mode is based on chain type and dynamic change mechanism of one-way and two-way interaction.
3. network type: considering the intersection of water conveyance lines, the risk transfer is not restricted by upstream and downstream, and there may be a risk transfer across structures.

The structural characteristics of the project determine its inherent vulnerability. When the project itself does not have fatal defects, it was resistant to external risk input and it will be damaged when the risk has not been disposed of and continuously accumulated to the limit value. Therefore, there is an ‘incubation period’ before the damage. The duration of damage and the speed of transmission are related to many factors, such as the stability of external environment and management’s coping ability. After taking reinforcement measures, the safety performance is improved, and the structure has ‘risk immunity’. The timeliness of this immunity is affected by the emergency level, time and many other factors. Therefore, the risk transfer of a water diversion project presents complexity.

2.2. Quantitative modeling tools in system dynamics

To quantify the risk transfer process, we need a method that can quantitatively analyze the interaction of risk factors in complex engineering systems, and comprehensively show the dynamic change process of system risk. Li (Li & Liang 2009) was also aware of the dynamic characteristics of the risk transfer process. Therefore, after putting forward the risk element transfer theory, combined with system dynamics, he successively put forward several risk transfer models of project management (Li *et al.* 2012, 2015a, 2015b).

Although many scholars have identified the operational risk factors of the water transfer project (Dehghani *et al.* 2021; Lei *et al.* 2021) and put forward various methods in risk control (AHP, FEMA, HACCP); most of them studied the interference of external risks in a static state. While Han (Han *et al.* 2018) established a risk evaluation system for a river-crossing structure, they proposed to divide the risk factors into static and dynamic ones for risk calculation. But the dynamic risk here is based on probability, and does not consider the change of the risk affected by time and other risks.

The change of risk not only refers to the relationship between various risk factors in a project, but also refers to the transmission and transfer of the risks of each structure through the water conveyance line. Aloini (Aloini *et al.* 2012) pointed out that if the relationship between risks is not identified and managed, it will bring large errors to the risk assessment, and some factors may be forgotten, ignored or underestimated, which reflects the importance of the relationship between risks.

How to quantitatively evaluate the dynamic changes and interaction of risks still needs further research.

Most of the approaches mentioned are based on linear causal thinking, thus leading to a limited representation of the multiplicity of interactions, dependencies and constraints in the diverse factors. Considering such limits, the use of system

dynamics modelling (SDM) techniques (Forrester 1997) could help in investigating the dynamic behaviours and structural characteristics of complex systems over time by converting the whole system into a set of variables interconnected also through feedback loops (Agnew *et al.* 2018; Zomorodian *et al.* 2018). The theory has been mainly applied to national policy research, resource allocation and other macro fields.

Gradually, due to the advantage of considering the impact of different elements (subsystems) on system security, the theory has been applied to risk safety management research (Maryani *et al.* 2015; Pitchaimuthu *et al.* 2019). At the same time, it can also achieve dynamic and quantitative prediction, making up for the shortcomings of linear qualitative, static and chain evaluation methods.

3. ESTABLISHMENT OF THE RISK TRANSFER MODEL

3.1. Basic assumptions

It was found that there are similarities between the transmission of engineering risk and infectious diseases (Riley 2007). Based on the process of infectious disease transmission model (Stone *et al.* 2007), some scholars have established the enterprise risk diffusion model (Ming and Zhan 2009).

When a structure is exposed to external risk, it will break the balance into a perilous state, and pass it to the others through the water conveyance line.

It should be noted that the transmission of infectious diseases is greatly affected by human activities. And the transmission direction and range are random, while the risk transmission between buildings on water transmission lines is directional (Figure 1).

Before establishing the model, the following assumptions are made:

1. Each node is divided into five states (Figure 2). Low risk state (P_I); Medium risk state (P_{II}); High risk state (P_{III}); Extremely high risk state (P_{IV}); The immune state (P_0) is the recovery state, which has been interfered by the risk but died out by its own regulatory capacity. The P_0 state has timeliness. Although the strengthened structures have returned to normal operation state, and even the ability to resist risks has been improved, they will return to the risk transfer system after a certain service life.
2. The transmission of risk is affected by both promoting and hindering factors. Promotion factors refer to the factors that can promote the risk transmission. The risks of single building mainly come from the natural environment (s), engineering defects (g) and human activities (h). The risk input promotes the risk transmission, which is recorded as the promotion function $p(s, g, h)$. The improvement of management level (m) and emergency response level (e) can effectively hinder the risk escalation and diffusion, which is recorded as the hindrance function $f(m, e)$.
3. Similar to infectious diseases, the simultaneous interpreting of risks involves the contact rate (τ_p) between the structures, which is proportional to the arrangement distance (l). Suppose that the interference rate of the structures' transferred risk is ω , which is depend on the project quality.

Once a new point is damaged, it will become a new risk source and transfer the risk to the upstream and downstream. And the risk transfer path will form a closed loop, which is called 'risk feedback'. It is assumed that the feedback rate of risk transfer to upstream and downstream is λ_1 and λ_2 respectively. The above parameters are proportional to the promotion function $p(s, g, h)$.

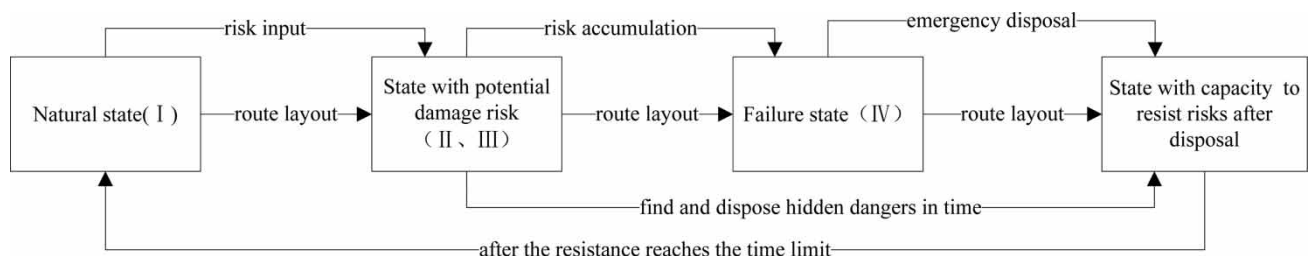


Figure 2 | The process of the risk on the water conveyance line.

4. Due to the regulation ability of the project itself, the risk can be gradually reduced. The risk recovery rate β_f is related to the engineering design and construction level. After the damage occurred and reinforcement measures were taken, the project has the capability to resist the risk again. At this time, the project is in the 'immune' state, and the immune rate α_f is related to the discovery time and rescue level. The above parameters can effectively prevent the risk transfer process, so they are proportional to the hindrance function $f(m, e)$.

In this paper, the simulation model of risk transfer is established by taking the canal section with the structure nodes $n = 3$ as an example (Figure 3). Table 1 shows the model parameters.

3.2. Parameter setting

In order to describe the change of state variables with time in Figure 3, a series of algebraic equations are used, which is called DYNAMO (dynamic model) language. For the simulation object in this paper, the equation is set as follows:

Initial risk R_0 = anthropogenic risk h + engineering defect risk g + environment risk s ;

Contact rate τ_{11} = constant k_1 distance L_{11} ;

Contact rate τ_{12} = constant k_2 distance L_{12} ;

Interference rate ω_{11} = constant k_2 (engineering defect risk g_{11}/R_d + constant k_1 distance L_{11}). R_d , which is the cumulative risk reaches extremely high risk state P_{IV} .

Interference rate ω_{12} = constant k_2 (engineering defect risk g_{12}/R_d + constant k_1 distance L_{12}). R_d , which is the cumulative risk reaches extremely high risk state P_{IV} .

Real-time risk R_{11} = INTEG(IF THEN ELSE(real-time risk level of the first damaged structure $R < R_d$, 0, $\omega_{11} * \tau_{11} * R$), Initial risk R_{110}). When R is lower than R_d , there is no risk transmission on the water transmission line.

Real-time risk R_{12} = INTEG(IF THEN ELSE(real-time risk level of the first damaged structure $R < R_d$, 0, $\omega_{12} * \tau_{12} * R$), Initial risk R_{120}).

Feedback rate λ_{11} = IF THEN ELSE($R_{11} \geq R_d$, 1, 0). When R is no lower than R_d , it is considered that the building begins to transfer the risk, and the risk is fed back to the building that first starts to transfer the risk;

Feedback rate λ_{12} = IF THEN ELSE($R_{12} \geq R_d$, 1, 0).

Level of emergency response e = IF ELSE THEN('emergency response time', $f(m, e)$, 0);

Risk resistance α = IF THEN ELSE($e \geq 1$:OR: $m \geq 1$, $f(m, e)$, 0);

Based on the above formula, the real-time risk level of the first damaged structure R = INTEG((risk input rate r + $R_{11}\lambda_{11} * \tau_{11} + R_{12}\lambda_{12} * \tau_{12}) * \omega - \alpha$, initial engineering safety level R_0).

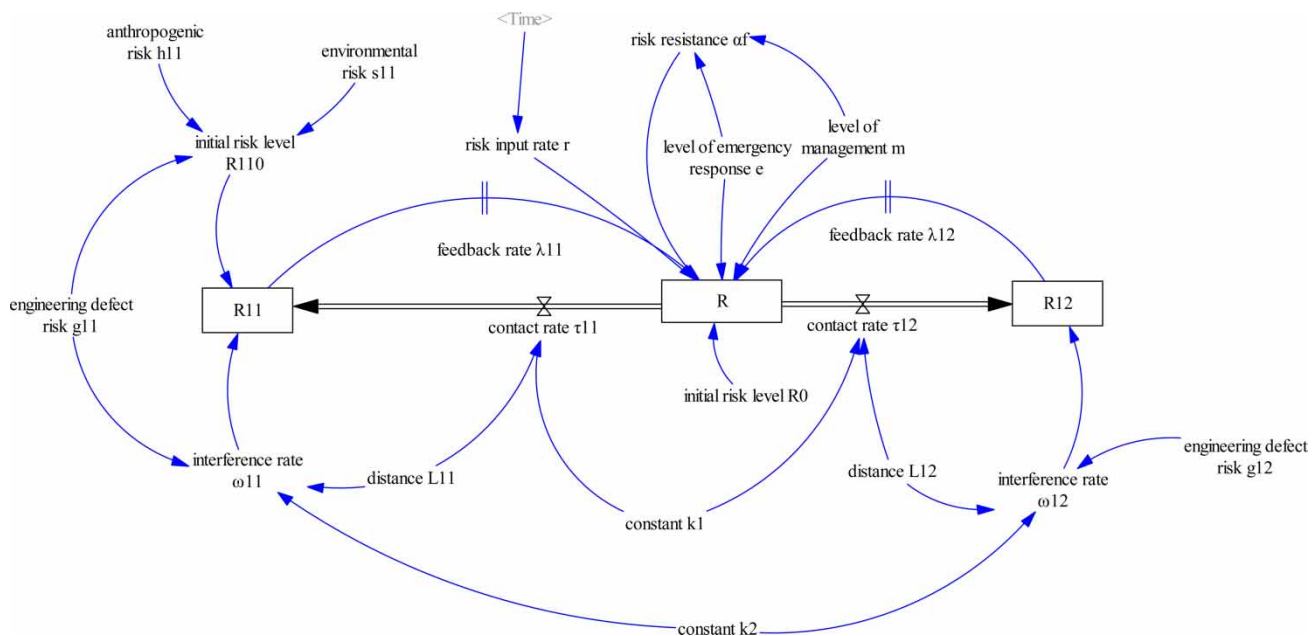


Figure 3 | Risk transfer dynamic simulation model ($N = 3$).

Table 1 | The parameter description of $n = 3$ risk transfer dynamic simulation model

Parameter	Meaning	Attribute	Remark
s	environmental risk	C	obtained through risk assessment (Thaheem & Marco 2012)
g	engineering defect risk	C	
h	anthropogenic risk	C	
m	level of management	C	related to management level
e	level of emergency response	A	related to the rescue time and disposal method
r	risk input rate	R	rainstorm, flood, earthquake, etc
L	distance between adjacent structures	C	constant
R0	initial risk level of the first damaged structure	A	related to natural environment, engineering defects and human activity risks
Rij0	initial risk level of the adjacent structures, $i = 1, 2$, refers the level of risk transmission; $j = 1, 2$, refers to upstream and downstream respectively	A	
R	real-time risk level of the first damaged structure	L	related to the initial risk level and risk input
Rij	real-time risk level of the adjacent structures, $i = 1, 2$, refers the level of risk transmission; $j = 1, 2$, refers to upstream and downstream respectively	L	
τ_p	contact rate between adjacent structures	A	proportional to distance
ω_j	interference rate, $j = 1, 2$, refers to upstream and downstream respectively	A	directly proportional to engineering defects
λ_{ij}	feedback rate, $i = 1, 2$, refers the level of risk transmission; $j = 1, 2$, refers to upstream and downstream respectively	A	directly proportional to the exposure rate and the probability of risk interference, and has a latency
α_f	risk resistance acquired after rescue	A	directly proportional to the management level and emergency disposal level
Constant k1	relationship coefficient between L and τ_p	C	related to the twists and turns of the line, water conveyance flow and other factors
Constant k2	relationship coefficient between g and ω_j	C	normalization coefficient of engineering defect G

Note: C-constant, A-auxiliary variable, R-rate variable and L-state variable.

3.3. Discussion of equilibrium point

From the above equations, it is shown that risk transmission may have a trend of extinction.

To figure out whether the risk is gradually accumulating or disappearing, it is necessary to determine the risk equilibrium point. According to the definition of state variables L, differential equation models are established for R_{11} , R_{12} and R respectively:

$$\begin{cases} \frac{dR_{11}}{dt} = \omega_{11}\tau_{11}R \\ \frac{dR_{12}}{dt} = \omega_{12}\tau_{12}R \\ \frac{dR}{dt} = (r + R_{11}\lambda_{11}\tau_{11} + R_{12}\lambda_{12}\tau_{12})\omega - \alpha \end{cases} \quad (1)$$

Obviously, when $\frac{dR_{11}}{dt}$, $\frac{dR_{12}}{dt}$, $\frac{dR}{dt}$ are equal to zero, there will be no risk transmission within the system, and the system reaches a balanced state. Combined with the engineering practice and model assumptions, there may be two possibilities:

1. No-risk transfer equilibrium point: when the initial risk R_{ij} of each building is less than R_d and there is no external risk input r . there is no trigger condition for risk transfer, and the system is in a stable state all along.

2. Risk transfer equilibrium point: once the project is continuously affected by external risks and appropriate emergency measures are not taken, no matter what state the building risk is in, there will be a breach of damage and trigger the transmission of risk.

For the system with $N = 3$ and only one structure subject to the external risk input (Figure 3), the equilibrium point will exist only when Equation (2) is established:

$$(r + R_{11}\lambda_{11}\tau_{11} + R_{12}\lambda_{12}\tau_{12})\omega = \alpha \quad (2)$$

From the significance of the variables in the formula, under the condition of continuous external risks input, only by taking human intervention measures that the structures regain the risk resistance α can slow down or even stop the further diffusion of risks. α and r determine the scope and trend of risk transmission.

Therefore, assuming the relative relationship between α and r , the other parameters remain unchanged, the following discussion is carried out (Figure 4):

- (1) $\alpha = 0$ and $r \neq 0$: In the case of continuous external risks input, R and R_{11} will continue to rise without control measures, the risk will be stably transferred to adjacent buildings;
- (2) $\alpha = r \neq 0$: It is assumed that the structure regains the ability to resist the input risk after reinforcement. At this time, although the structure will not be affected by environment, its risk will continue to be transmitted to the other structures because the damage has occurred. When R_{11} reaches the damage limit R_d , the risk will be fed back to R . Therefore, the risk of each point remains increasing and the risk transfer continues;
- (3) $\alpha > r \neq 0$: The level of emergency response is still not up to the degree that it can resist external input risk and restore the safety of the structure at the same time, the risk R_{ij} is still increasing, but the growth rate is decreasing. If the level of emergency disposal and reinforcement can greatly improve the safety of the project and keep the building free from external risks ($\alpha \gg r \neq 0$), there is no trigger event of risk transmission in the system. At this time, the risk transmission process will be blocked. The structures that cannot be reinforced in time will maintain a stable level, that is, the risks will not die out and remain in the system.

4. CASE STUDY

4.1. Description of the case study

The activities described in the present paper were performed in one of the case studies of the middle route of the South-to-North Water Transfer Project, namely the Lushan section case study. This section is located in Lushan County, Henan Province, and crosses 6 large rivers (the drainage area above the river channel intersection is $>20 \text{ km}^2$) and 24 small rivers (the drainage area above the river channel intersection is $<20 \text{ km}^2$). The total length of the line in this section is 43.34 km (Table 2). in which the problem of expansive soil (rock) is more prominent and Shahe aqueduct is also a key risk focus.

4.2. System dynamics modelling

Assuming that Penghe culvert aqueduct is the receptor of risk input, when it is damaged, its risk will be transferred to the adjacent structures (Figure 5). The structures are evaluated according to the literature (Thaheem & Marco 2012), and the results R and G can be used as the initial parameters of the model (Table 2).

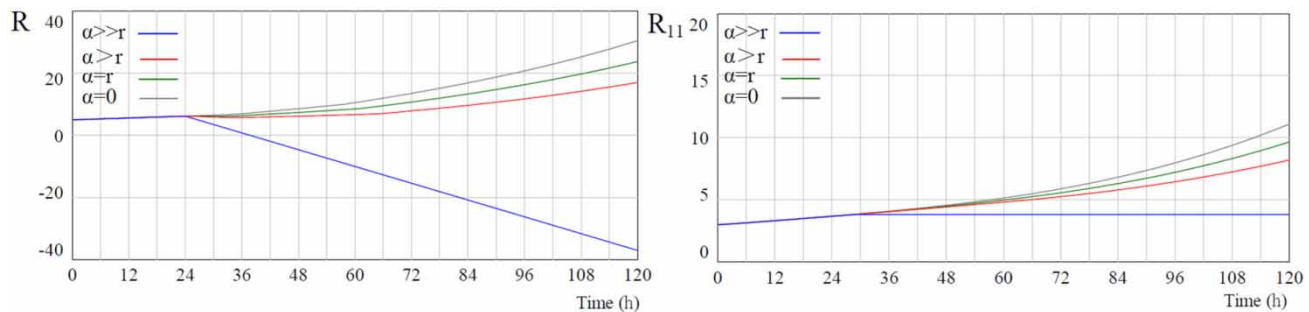


Figure 4 | Impact of different α on the risk level of each structure.

Table 2 | Division of line buildings of Lushan Management Office

Number	Name	Real-time risk	Input parameters	Type	Start station	End station	Length (m)
1	Channel 1	R31	R310 = 1.197 L31 = 356 g31 = 0.6655	Full excavation channel	K215 + 811	K216 + 460	887
2	Huihe inverted siphon	R21	R210 = 1.26 L21 = 14,952.9 g21 = 0.7015	Inverted siphon	K216 + 698	K217 + 054	356
3	Channel 2	R11	R110 = 1.200 L11 = 310 g11 = 0.6045	Expansive soil; half cut and half fill channel	K217 + 054	K232 + 006.86	14,952.86
4	Penghe culvert aqueduct	R	R0 = 1.199 g = 0.503	Aqueduct	K232 + 006.86	K232 + 316.86	310
5	Channel 3	R12	R120 = 1.136 L12 = 6,222.14 g12 = 0.6045	Half cut and half fill channel	K232 + 316.86	K238 + 140	6,222.14
6	Feihe inverted siphon	R22	R220 = 1.137 L22 = 404.01 g22 = 0.503	Inverted siphon	K238 + 140	K238 + 544.01	404.01
7	Channel 4	R32	R320 = 1.258 L32 = 3,341 g32 = 0.7265	High-fill channel	K238 + 544	K241 + 885	3,341
8	Shahe aqueduct	R42	R420 = 1.866 L42 = 7,520 g42 = 1.135	Aqueduct	K241 + 885	K249 + 405	7,520
9	Channel 5	R52	R520 = 1.521 L52 = 9,349 g52 = 0.9895	Half cut and half fill channel	K249 + 405	K258 + 754	9,349

The real-time risk R of Penghe culvert aqueduct = $\text{INTEG}((\text{risk input rate } r + \text{the real-time risk } R_{11} \text{ of channel 1} * \lambda_{11} * \tau_{11} + \text{the real-time risk } R_{12} \text{ of channel 2} * \lambda_{12} * \tau_{12}) * \omega - \alpha, \text{ initial engineering safety level } R_0)$.

4.3. Discussion

Combined with the accident data of the South-to-North Water Transfer Project collected in this study, it is found that the time from discovery to disposal of most cases is 1–2 days. The safety state of the project changes greatly during this time period. Considering the general duration of rainfall, the simulation model time is set as 48 hours in this paper. After 24 hours, the management found the dangerous situation of Penghe culvert aqueduct and then took rescue and reinforcement measures to simulate the following four situations: (i) $\alpha = r = 0.05$; (ii) $\alpha = 0.1, r = 0.05$; (iii) $\alpha = 1, r = 0.05$; (iv) $\alpha = 5, r = 0.05$.

The real-time risk level of each structure at the 48th hour is shown in [Figure 6](#).

(i) When $\alpha = 0.05$ or 0.1 , the results are basically consistent and the rate of risk level R and R_{11} increase exponentially. Although the growth rate of others is relatively slow, the upstream is obviously impacted. Even if rescue measures are taken, the upstream risk level R_{11} , R_{21} and R_{31} will be affected after 2.5, 6 and 10 hours respectively. Moreover, with the continuous accumulation of R_{31} risk, the dangerous situation will even be transmitted to its upstream. This is due to the lack of effective risk control.

(ii) When $\alpha = 1$, as shown, the trend of risk level R_{ij} is basically consistent with the former, but the growth rate slows down with the increase of rescue efforts. It is worth noting that R_{22} is not affected at this time, which indicated that the scope of risk transmission is reduced and emergency measures are effective.

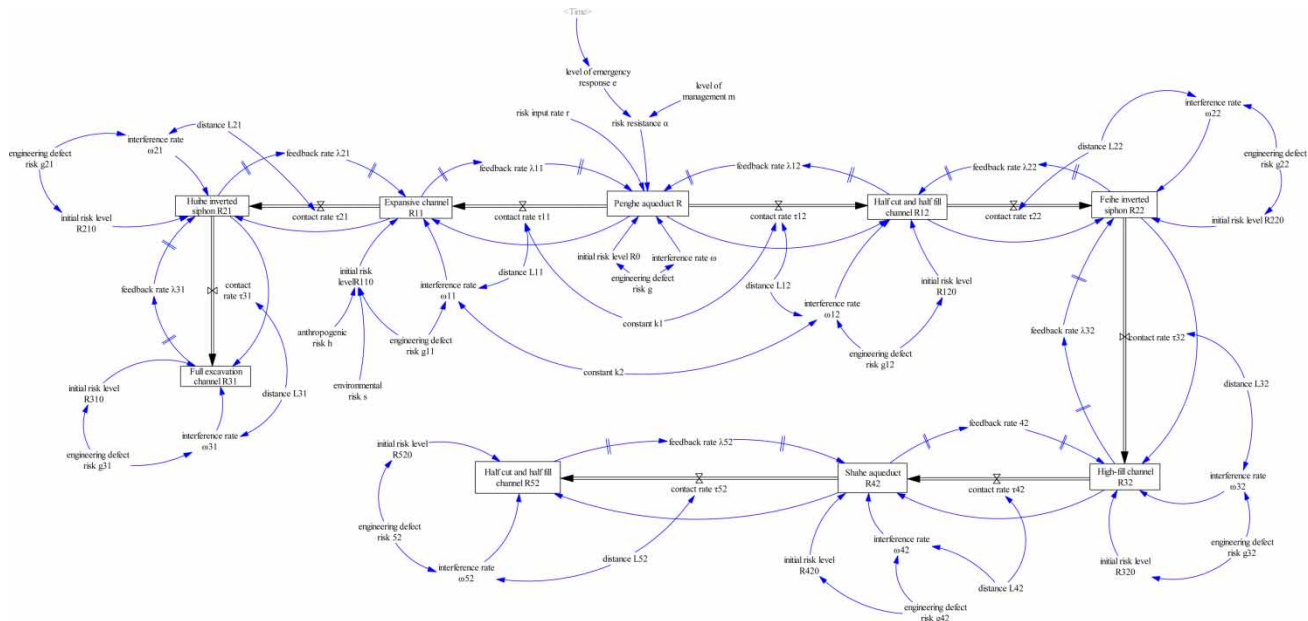


Figure 5 | Dynamic simulation model of risk transfer in Lushan section.

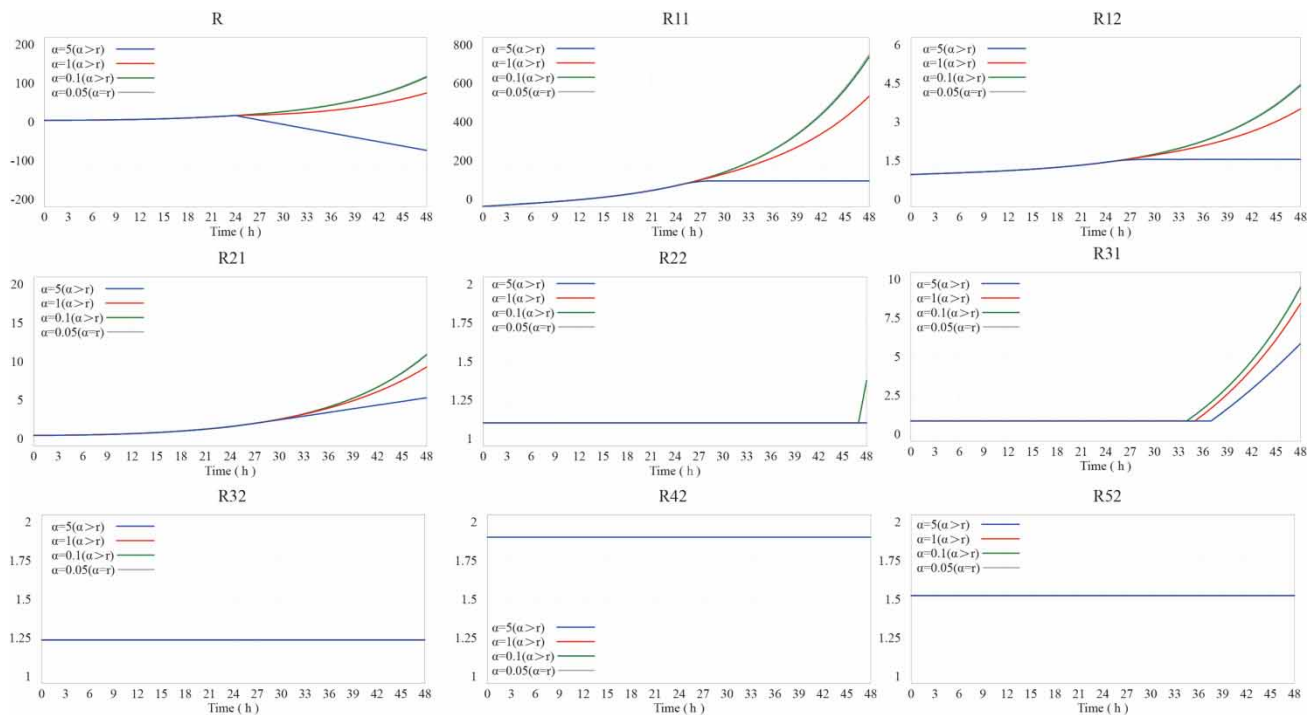


Figure 6 | The change of real-time risk on the water transmission line.

(iii) When $\alpha = 5$, that is, the emergency rescue efforts far exceed the risk input rate, the R value decreases rapidly, and even a negative value (safe state) appears. The danger is stopped immediately, and the real-time risk of other buildings remains unchanged.

5. CONCLUSION

Stemming from the need to drive the risk management of water transfer project, the present paper proposes a SDM of risk chain transmission based on system dynamics, in which the mathematical relationship between variables is expressed in the form of stock flow diagram. The risk transfer parameters between buildings on the water transmission line are proposed for the first time, and the scope and degree of risk transfer are quantitatively simulated. The establishment of the model can support the emergency decision-making of building groups in a flood period.

Specifically, this work aims to go beyond the inherent thinking that the traditional engineering risk analysis is only carried out for a single structure. Especially for the projects with strong correlation of structure, traditional analysis methods often underestimate the risk level because they do not consider the transformation of projects from risk receptor to risk source. Therefore, this model is based on the risk analysis of single structure, highlighting and valuing the risks transferred between structures.

The adopted approach is based on three steps: (i) the assessment the current risk level of a single structure or a canal section based on the patrol inspection; (ii) the determination of main input risk sources; (iii) the development of a SDM, capable of analyzing the real-time risk changes of different buildings under different emergencies and response conditions from a multi-dimensional perspective.

To verify the validity of the model, this paper intercepts a section located in Lushan County in the middle route of the South-to-North Water Transfer Project for dynamic simulation. Under the assumed risk input conditions, changing the intensity parameters of human intervention can effectively organize the development of risk on the water transmission line.

There are still many parts worth studying to improve the accuracy of the model, such as the setting of risk input rate. In recent years, frequent extreme rainstorm events have become the main reason for the failure of water conservancy facilities. Therefore, experimental study need be conducted for simulating the impact of rainfall on building risk changes, to make the model more practical. Due to the complexity of the actual situation, this paper only studies the impact of one structure failed on adjacent structures. After improving the accuracy of model parameters, more situations can be simulated since the SDM has high flexibility in scenario deduction..

ACKNOWLEDGEMENT

This study is supported by the National Natural Science Foundation of China (No. U204020043), National Key Research and Development Program of China (No. 2017YFC0405006) and Fundamental Research Funds for the Central Research Institute (No. Y721010).

DATA AVAILABILITY STATEMENT

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

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First received 27 October 2021; accepted in revised form 11 February 2022. Available online 25 February 2022