Water Research 85 (2015) 31–37

Contents lists available at ScienceDirect

Water Research

journal homepage: www.elsevier.com/locate/watres

How to manage future groundwater resource of China under climate change and urbanization: An optimal stage investment design from modern portfolio theory

Shanshan Hua [a, b], Jie Liang [a, b, *], Guangming Zeng [a, b, **], Min Xu [c], Chang Zhang [a, b], Yujie Yuan [a, b], Xiaodong Li [a, b], Ping Li [a, b], Jiayu Liu [a, b], Lu Huang [a, b]

[a] College of Environmental Science and Engineering, Hunan University, Changsha 410082, PR China
[b] Key Laboratory of Environmental Biology and Pollution Control, Hunan University, Ministry of Education, Changsha 410082, PR China
[c] Chinese Academy for Environmental Planning, Beijing 100012, PR China

ARTICLE INFO

Article history:
Received 3 June 2015
Received in revised form
20 July 2015
Accepted 3 August 2015
Available online 6 August 2015

Keywords:
Groundwater management
Modern portfolio theory
Climate change
Urbanization
China

ABSTRACT

Groundwater management in China has been facing challenges from both climate change and urbanization and is considered as a national priority nowadays. However, unprecedented uncertainty exists in future scenarios making it difficult to formulate management planning paradigms. In this paper, we apply modern portfolio theory (MPT) to formulate an optimal stage investment of groundwater contamination remediation in China. This approach generates optimal weights of investment to each stage of the groundwater management and helps maximize expected return while minimizing overall risk in the future. We find that the efficient frontier of investment displays an upward-sloping shape in risk-return space. The expected value of groundwater vulnerability index increases from 0.6118 to 0.6230 following with the risk of uncertainty increased from 0.0118 to 0.0297. If management investment is constrained not to exceed certain total cost until 2050 year, the efficient frontier could help decision makers make the most appropriate choice on the trade-off between risk and return.

1. Introduction

Groundwater is one of the most valuable natural resources, which supports human health, economic development and ecological diversity (Jha et al., 2006). However, overexploitation and poor management have contributed to infamous groundwater depletion problems and less publicized groundwater quality deterioration (Sun et al., 2009; Lijzen et al., 2014). Moreover, changes in water quantity and quality are considered to have strong environmental and socio-economic consequences. Under the intensive human activities and environmental changes, groundwater pollution control becomes an arduous issue for groundwater management (Hu et al., 2010a). It is necessary to take steps toward a sustainable and proactive management of the groundwater resources. Groundwater vulnerability as an important factor to be considered in conjunction with groundwater quality is defined as the sensitivity of a groundwater system to pollution (Butscher and Huggenberger, 2009). Such a concept allows for vulnerability to be a guiding factor in the process of groundwater management.

Meanwhile, groundwater vulnerability is affected by climate change and urbanization through the alteration of water cycle (Pasini et al., 2012; Döll, 2009). Climatic factors, such as temperature, precipitation and evaporation, will directly alter groundwater vulnerability through interaction with surface water, net recharge and groundwater levels (Carlson et al., 2011). Urbanization often modifies the land surface and the induced changes may lead to a sharp decline or rise in groundwater level and deterioration in groundwater quality (Sekhar et al., 2013; Bai et al., 2012a). Understanding how climate change and urbanization may affect groundwater resources could provide insights for creating sustainable management plans.

However, unprecedented uncertainty stemming from climate change and urbanization makes it difficult to implement groundwater planning paradigms according to the groundwater

* Corresponding author. College of Environmental Science and Engineering, Hunan University, Changsha 410082, PR China.
** Corresponding author. College of Environmental Science and Engineering, Hunan University, Changsha 410082, PR China.
E-mail addresses: liangjie82@163.com (J. Liang), zgming@hnu.edu.cn (G. Zeng).

http://dx.doi.org/10.1016/j.watres.2015.08.007
0043-1354/

vulnerability (De Cian and Massimo, 2012; Pressey et al., 2007; Blazquez and Nunez, 2013). How to account for uncertainties in the management of groundwater resource will be a key issue. The approach is conspicuous, which adapts a stage investment tool from Modern portfolio theory (MPT) to exploit information about covariance in future groundwater conditions and applies that tool to explicit targeting of management investments (Ando and Mallory, 2012). Also, it can manage the risk that uncertainty attaches to the future outcomes of current management investments (Yang et al., 2013). MPT balances risk and return in determining the optimal allocation of an investor's overall investment portfolio across various investment alternatives (Rankovic et al., 2014). Its basic principle is to maximize expected future return for the portfolio or minimizing overall portfolio risk in the future. By correctly choosing portfolio weights (fractions of total investment) among each stage one can find portfolios that are efficient in the sense that for a given level of return (Crowe and Parker, 2008).

Our case study for using MPT in stage investment management is China which has been experiencing significant changes in both climate and urbanization (Bai et al., 2012b). China is faced with regional water crises. Water shortages, coupled with increasing demands from industrial, agricultural, and domestic users, are putting intolerable pressures on national resources, and water wastage and pollution are further exacerbating the problem (Burke, 2000; Candela et al., 2009). Increasing water demand has resulted in severe groundwater overdraft, groundwater level decline and groundwater quality degradation in China. But the current management system is not able to provide an effective and efficient solution. The management institutions are locally designed and the key management instruments are not integrated (Shen, 2015; Zhu, 2013; Gong et al., 2000). China lacks distinct groundwater management plan in the future. To improve groundwater management, the concept of stage investment management and an integrated groundwater management investment plan must be developed.

In this paper, we develop a stage investment portfolio model from MPT to characterize optimal targeting of management policies and investments in the future. Groundwater vulnerability index (GVI) is employed as the benefit of expected return to guide groundwater management priority setting in China. GVI outcomes have been modeled (Supporting Information) for four different future climate scenarios. According to China's situation, the management scenarios are planned to have three managed stages. The first stage is from 2020 to 2030, the second stage is from 2030 to 2040, and the third stage is from 2040 to 2050. Under almost all portfolio stages, areas with moderate, high and very high vulnerability will dramatically expand, and areas with low or very low vulnerability will substantially shrink, as can be seen from the Figure S3 (Supporting Information). This geographic shift will increase the difficulty of groundwater management. To effectively and efficiently manage groundwater resource, MPT is used to maximize expected future return of GVI for the portfolio while minimizing overall portfolio risk in the future. The objective of the study is to determine the weights for allocating the groundwater management investment to each managed stage in the uncertain future, depending on the sign of the forecasts of the GVI.

2. Materials and methods

2.1. Structural/description of stage investment portfolio model from MPT

In this paper, a stage investment portfolio model from MPT is developed. Fig. 1 depicts a conceptual model of our approach. The values of GVI are used to estimate the groundwater quality in future stages under different climatic conditions. These estimates are then set as inputs in the stage investment portfolio model. It is used to find the optimal weights of allocating capital to each stage that maximize expected future return while minimizing overall risk.

The portfolio model requires three types of variables: (1) the expected return of each potential asset in the portfolio; (2) the expected variance of each asset's return over time; and (3) the expected covariance among asset returns over time. In the stage investment portfolio model, corresponding proxies for the above variables are: (1) the expected return of each managed stages equals the value of projected GVI, under all considered climate scenarios; (2) the expected variance of each managed stages equals its variance in return over all considered climate scenarios variance; and (3) the expected covariance of each managed stage with other managed stages equals its covariance in return across all climate scenarios.

2.2. Stage investment portfolio analyses

In investment management terms, it is not sufficient to simply say that you want to achieve the best returns possible. It is impossible to separate the pursuit of the best returns from the consequential exposure to risk that you will face along the way (Marinoni and Adkins, 2009). In the formulation of portfolio model, the objective function is to minimize the variance and covariance (i.e., the risk) of the selected assets in stochastic market environments. Analogously, our objective function of the stage investment portfolio model is to minimize the expected variance and covariance of the portfolio of projection GVI, over a variety of possible climate scenarios.

Our specific numerical implementation of MPT solves for the efficient fractions of all period to invest in each stage (also known as portfolio weights). The objective is to maximize expected of GVI while minimizing overall risk of uncertainty in the future. Formally,

$$\min X^T \Sigma X, \;\; \text{Subject to} : \sum_{i=1}^{n} X_i E(R) \geq R^*, \quad \sum_{i=1}^{n} X_i = 1.0, \quad R_{\min} \leq R^* \leq R_{\max} \tag{1}$$

where the X_i is the weights of the portfolio of investment in each managed stage, belonging to the decision variables; T is the transpose operator; $E\,(R)$ is the expected return of each managed stage, over all climate scenarios; R^* is the desired expected return for the entire portfolio; Σ is the covariance matrix of R; $R_{\max}$ is the maximum value of the desired expected return for the entire portfolio; $R_{\min}$ is the minimum value of the desired expected return for the entire portfolio.

Equation (1) minimizes the total covariance (risk) associated with the managed stage portfolio, ensuring that the portfolio has an expected return of R^* and the portfolio's weight sum to 1. We trace out the shape of the efficient frontiers by solving the problem in Equation (1). In this paper, we set $R_{\max} = 0.6230$ (the maximum value of projected GVI from Supporting Information) and $R_{\min} = 0.6065$ (the minimum value of projected GVI from Supporting Information) and used 50 evenly spaced values between the minimum and the maximum to construct the efficient frontier in the benefits analysis. The frontcon routine in the Financial Toolbox of the Matlab R2011a release is used to calculate above.

2.3. Benefits

We translate GVI forecasts of 2030, 2040 and 2050 from the maps into values on a gridded map of China such that each grid square covers 16 km^2, and calculate the average GVIs of the grid

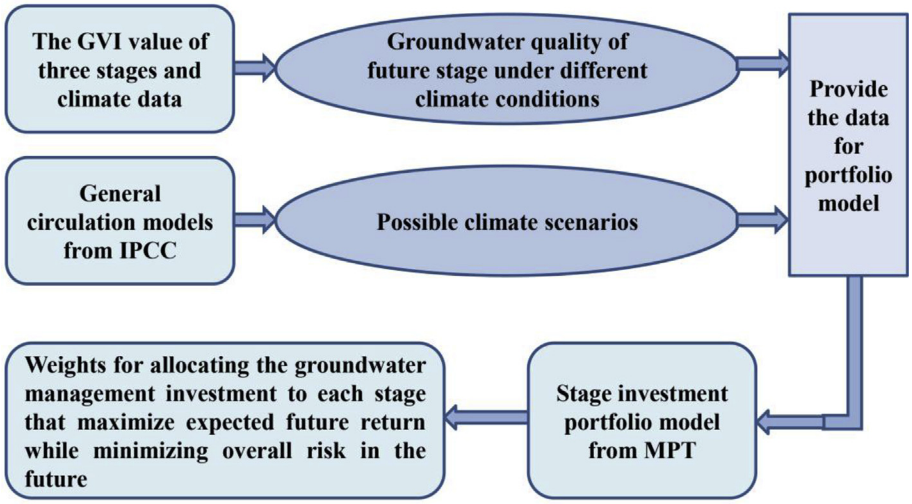

Fig. 1. Conceptual model of approach to allocate the weights for groundwater management under climate change.

squares in China for each climate scenario (note that the future GVI varies widely depending on the climate change outcomes). The assumed probabilities for our probability-distribution scenarios are in Table 1 along with the expected outcomes of GVI across three future stages. In the benefit analyses, we define the return as R = GVI and the expected GVI in each stage is defined as

$$E[GVI_i] = \sum_j P_j \times GVI_{ij} \quad \text{for all climate scenarios } j \tag{2}$$

That is, the expected GVI in year i is the sum of the probabilities (P) of each climate scenario times the realized GVI in year i for climate scenario j.

2.4. Data source

The data of GVI are from the Supporting Information projected with a revised DRASTIC model, DRASI. Each of the DRASI factors represents Depth-to-water table, Recharge (net), Aquifer media, Soil media, Impact of the vadose zone, respectively. The baseline data of depth-to-water table (D) are collected from *China Groundwater Level Yearbook for Geo-environmental Monitoring*. The baseline Recharge (net) (R) data are obtained by interpolating the 2010-year mean of annual precipitation (mm/year) from 24 representative rainfall stations. The aquifer media parameter (A) is prepared using a subsurface geology map. The soil media parameter (S) is prepared using a geological map from The National Soil Database (NSDB) http://sis.agr.gc.ca/cansis/nsdb. The impact of vadose zone (I) is prepared from the lithological cross-sections obtained from the geophysical data.

The scenarios of RCP2.6, RCP4.5, RCP6.0 and RCP8.5 proposed by the Intergovernmental Panel on Climate Change fifth Assessment Report (IPCC-AR5) are adopted and applied to our study. The four scenarios are used as input to assess the future groundwater vulnerability and the scenarios for optimal portfolio analyses. And the precipitation and the evaporation projection dataset under the four scenarios (the result of IPCC's AR5 assessment report) will be used to estimate the future groundwater net recharge and depth-to-water table.

Table 1
Basic parameters for optimal portfolio analyses.

	RCP2.6	RCP4.5	RCP6.0	RCP8.5
Probabilities of climate outcomes[a]				
Uniform	0.25	0.25	0.25	0.25
Average groundwater vulnerability index (GVI)[b]				
First stage[c]	0.646	0.572	0.634	0.640
Second stage	0.637	0.592	0.623	0.626
Third stage	0.624	0.605	0.611	0.586

[a] It is difficult to say how likely each of the four climate scenarios are. Such probabilities depend, for example, on implementation of climate-change mitigation policy, which is uncertain in nature. Thus, we consider one sample probability distribution to demonstrate the sensitivity of optimal portfolio analysis to assumptions about outcome probabilities: One distribution, denoted "uniform," assumes each climate scenario is equally likely to occur.
[b] GVI values are taken from Ref. 16; stages variances and covariances are calculated by the authors.
[c] Portfolio managed stages in the future year of China.

3. Results

GVI outcomes have been modeled for four future climate scenarios in three managed stages (2020–2030, 2030–2040, and 2040–2050). The modeling finds that the values of GVI shift markedly as can be seen from the Figs. 2 and 3.

The resulting efficient frontier by finding the composition of groundwater management investment, illustrating the tradeoff between desired return (maximizes the expected value of the portfolio's GVI) and risk (measured as total covariance of return) is presented in Fig. 4. Some portfolio points on these efficient frontiers are highlighted. Table 2 contains detailed information about each of these highlighted portfolios. Portfolios with the highest expected values for GVI also have the most uncertainty associated with their outcomes. Thus, the efficient frontier in Fig. 4 displays a typical upward-sloping shape in risk/expected benefit space. Starting from point A and continuing to point E, efficient frontiers require more risk and more desirable higher returns. Risk increases from 0.0118 to 0.0297 and expected value increases from 0.6118 to 0.6230 (Table 2). Table 2 shows the portfolio weights of three managed stages under the different risks and benefits. In the lowest risk situations, the investment weights of three managed stages are 0, 37% and 63% respectively. However, in the highest expected benefits situations, all investment should be invested in the first stage. If management investment is constrained not to exceed some total cost until 2050 year, to maximize expected benefits, the decision maker could put more investment in stage of 2020–2030 with the highest expected value of GVI to accompany much more outcome variation. To minimize the uncertainty, we move from

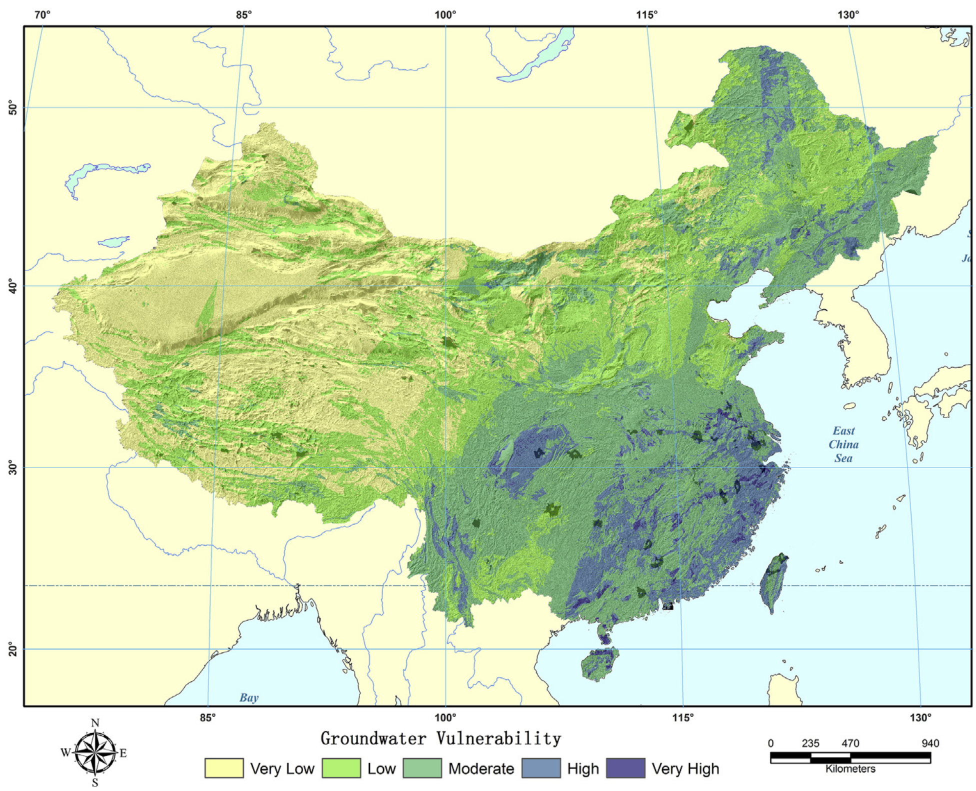

Fig. 2. Groundwater vulnerability in China for the baseline period (year 2010).

point E to point A along the efficient frontier, we see that risk reduction is accomplished in this situation by shifting some investment out of 2020–2030, and into 2030–2040 and 2040–2050.

4. Discussion

The results show that despite high uncertainty surrounding the future groundwater management. By applying MPT, management planning can be implemented to effectively reduce the risk of future uncertainties. Our analysis found that the efficient frontier of benefit analysis is remarkably close to the real results. When conducting investment management over groundwater in first managed stages, the quality of groundwater will become better with an increased uncertainty. Whereas, when doing the management in the second or third managed stages, the quality of groundwater will become worse but with a decreased uncertainty. Existing literature also suggests that the quality of groundwater will become worse if we do the management in a later stage (Rakhmatullaev et al., 2010; Rejani et al., 2008; Hu et al., 2010b). Meanwhile, China has invested about 35 billion in order to promote the process of groundwater management from 2011 to 2020.

If management investment is constrained not to exceed some total cost, MPT can perform very well with best optimal portfolio to manage future groundwater between groundwater quality and uncertainty. It provides the best investment weights of three stages for groundwater management. It will be decided by the decision makers to maximize the expected returns for a given level of uncertainty or minimize uncertainty for a given expected level of returns. Meanwhile, the investment proportions under uncertainty remain ambiguous. The results should be considered suggestive rather than conclusive in the process of management. To improve groundwater management, a distinct groundwater management plan on the future must be developed (Jha et al., 2006; Sophocleous, 2009). The existing systems need to be restructured to clarify relationships and functions. A reasonable management system is required and capacity building must be strengthened.

In planned stage of groundwater management for allocation of investments, MPT follows a general strategy of seeking robust solutions. It can help planners make strategic decisions on investment management more effectively than simple diversification schemes. It also can incorporate other factors to guide the groundwater management setting, such as GVI, and achieve the transformation from qualitative to quantitative. In addition, the probabilities of future climate scenarios are not explicitly required insofar as the probability of each scenario is assumed to be equal. However, one limitation to a general application of MPT is that the effect of interdependence in each managed stage is not absolutely isolated; it will make the portfolio weights of investment have a certain deviation. One potential limitation to a general application of MPT is that it is not readily adaptive to an immediate-term plan instead of a long-term plan in the process of groundwater management.

In future work, we would like to further develop the model to assess the future groundwater vulnerability under different emissions restrictions. It can help us better understand the distribution of future groundwater susceptible to pollution, so as to develop more effective management plan. It would also be interesting to analyze different reduction requirements on management risk for future years. To be able to realize the reduction of uncertainty in our assessment, an optimal portfolio design, such as MPT, will be needed (Pan et al., 2013). Management in groundwater continues to have different obligations with respect to different scenarios. Since future scenario is a complexity that needs to be staged out in a long run, it would also be interesting, in future studies, to use the MPT to

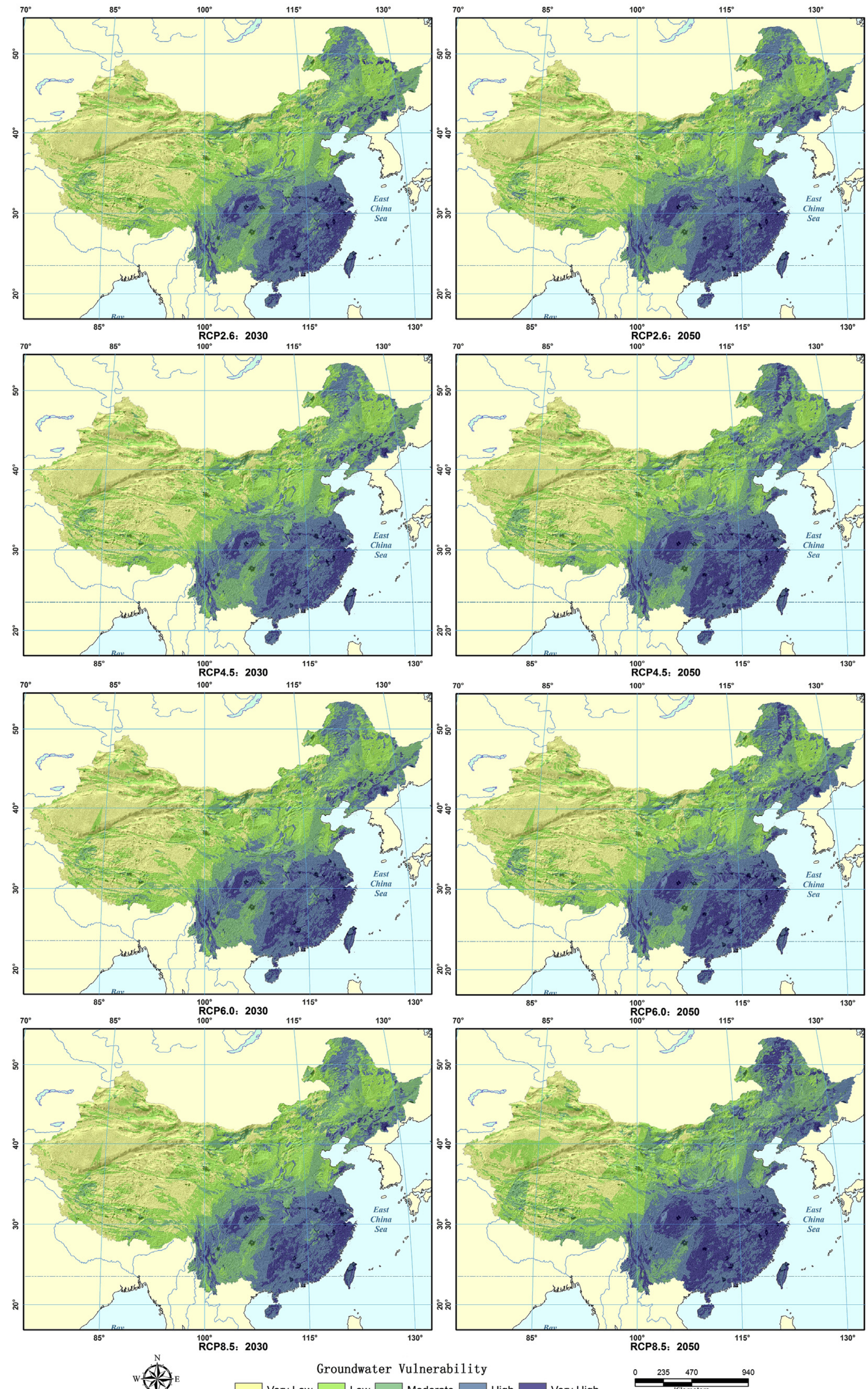

Fig. 3. Projected groundwater vulnerability in China for the scenarios of RCP2.6, RCP4.5, RCP6.0 and RCP8.5 in future periods (year 2030 and year 2050). Year 2040 is not shown in the picture, because it is a transition from 2030 to 2050.

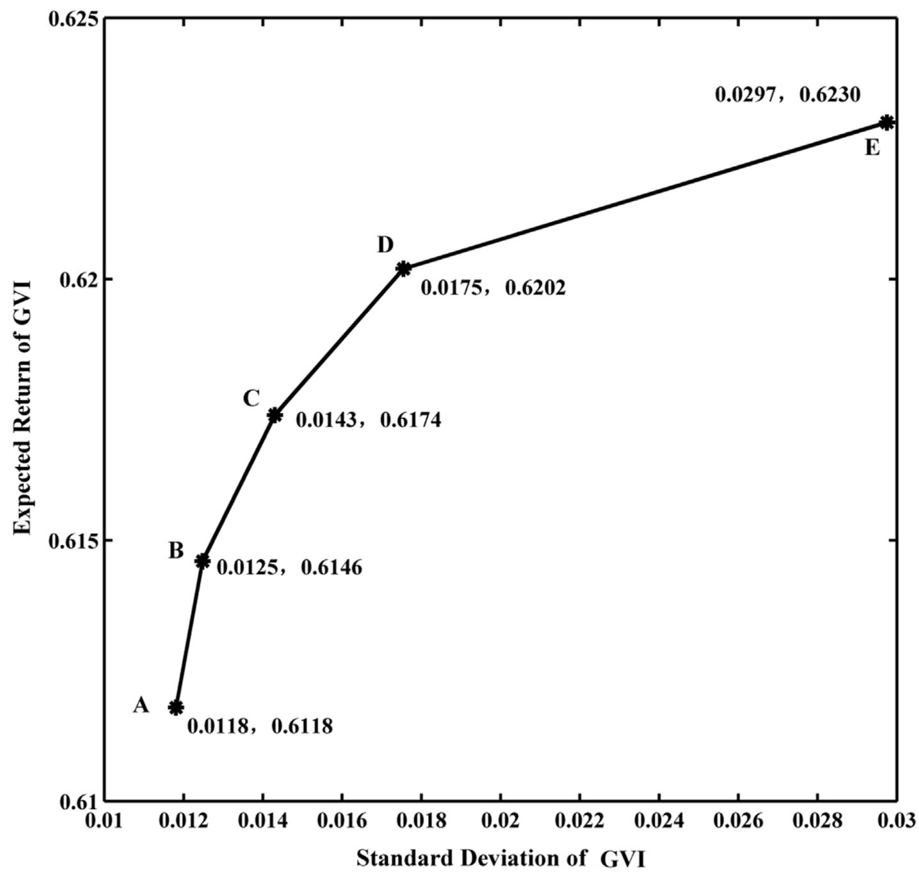

Fig. 4. Results of benefits portfolio selections. Point A to point E is the average expected values of NVI for the different standard deviation of NVI, respectively.

Table 2
Selected results of optimal portfolio analyses.

Point on figure	Portfolio weights[a]			Outcomes	
	First stage	Second stage	Third stage	∂^R	E[R]
A	0.0000	0.3691	0.6309	0.0118	0.6118
B	0.0000	0.5845	0.4155	0.0125	0.6146
C	0.0000	0.8000	0.2000	0.0143	0.6174
D	0.0666	0.9334	0.0000	0.0175	0.6202
E	1.0000	0.0000	0.0000	0.0297	0.6230

[a] The portfolio weights of investment in different managed stages under the different expects and risks.

analysis the uncertainty of groundwater vulnerability beyond 2050. This could include advanced management plan currently in an early stage of groundwater resource management. Such management options might also be essential in the future.

5. Conclusions

The study provides insights about the optimal weights of allocating capital to each managed stages that maximize expected future return for the portfolio while minimizing overall portfolio risk in the future. Groundwater vulnerability index is employed as the benefit of expected return because it is considered in conjunction with groundwater quality. The MPT is applied because it is a useful approach that can estimate the investment proportion for groundwater management. The results show that the analysis is remarkably close to the real results. The quality of groundwater will become worse if we do the management in a later stage. And the results of investment allocation will help China learn how to control its pollution in a more effective way under the high uncertainty attached to the climate change and urbanization. This is an important step in the process of making an effective national policy for groundwater.

Acknowledgments

This work is funded by the National Natural Science Foundation of China (51479072, 51009063, 51378190), the New Century Excellent Researcher Award Program (NCET-08-0181) from the Ministry of Education of China and the Program for Changjiang Scholars and Innovative Research Team in University (IRT-13R17).

Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.watres.2015.08.007.

References

Ando, A.W., Mallory, M.L., 2012. Optimal portfolio design to reduce climate-related conservation uncertainty in the Prairie Pothole Region. P. Natl. Acad. Sci. U.S.A. 109 (17), 6484–6489.
Bai, X., Chen, J., Shi, P., 2012a. Landscape urbanization and economic growth in China: positive feedbacks and sustainability dilemmas. Environ. Sci. Technol. 46 (1), 132–139.
Bai, X.M., Chen, J., Shi, P.J., 2012b. Landscape urbanization and economic growth in China: positive feedbacks and sustainability dilemmas. Environ. Sci. Technol. 46 (1), 132–139.
Blazquez, J., Nunez, M.N., 2013. Analysis of uncertainties in future climate projections for South America: comparison of WCRP-CMIP3 and WCRP-CMIP5 models. Clim. Dynam. 41 (3–4), 1039–1056.
Burke, M., 2000. Managing China's water resources. Environ. Sci. Technol. 34 (9),

218A-+.
Butscher, C., Huggenberger, P., 2009. Modeling the temporal variability of karst groundwater vulnerability, with implications for climate change. Environ. Sci. Technol. 43 (6), 1665–1669.
Candela, L., von Igel, W., Javier Elorza, F., Aronica, G., 2009. Impact assessment of combined climate and management scenarios on groundwater resources and associated wetland (Majorca, Spain). J. Hydrol. 376 (3–4), 510–527.
Carlson, M.A., Lohse, K.A., McIntosh, J.C., McLain, J.E.T., 2011. Impacts of urbanization on groundwater quality and recharge in a semi-arid alluvial basin. J. Hydrol. 409 (1–2), 196–211.
Crowe, K.A., Parker, W.H., 2008. Using portfolio theory to guide reforestation and restoration under climate change scenarios. Clim. Change 89 (3–4), 355–370.
Döll, P., 2009. Vulnerability to the impact of climate change on renewable groundwater resources: a global-scale assessment. Environ. Res. Lett. 4 (3), 035006.
De Cian, E., Massimo, T., 2012. Mitigation portfolio and policy instruments when hedging against climate policy and technology uncertainty. Environ. Model. Assess. 17 (1–2), 123–136.
Gong, H.L., Li, M.L., Hu, X.L., 2000. Management of groundwater in Zhengzhou city, China. Water Res. 34 (1), 57–62.
Hu, Y., Moiwo, J.P., Yang, Y., Han, S., Yang, Y., 2010a. Agricultural water-saving and sustainable groundwater management in Shijiazhuang irrigation district, North China plain. J. Hydrol. 393 (3–4), 219–232.
Hu, Y., Moiwo, J.P., Yang, Y., Han, S., Yang, Y., 2010b. Agricultural water-saving and sustainable groundwater management in Shijiazhuang irrigation district, North China plain. J. Hydrol. 393 (3–4), 219–232.
Jha, M.K., Chowdhury, A., Chowdary, V.M., Peiffer, S., 2006. Groundwater management and development by integrated remote sensing and geographic information systems: prospects and constraints. Water Resour. Manag. 21 (2), 427–467.
Lijzen, J.P., Otte, P., van Dreumel, M., 2014. Towards sustainable management of groundwater: policy developments in The Netherlands. Sci. Total Environ. 485–486, 804–809.
Marinoni, O., Adkins, P., 2009. Joint application of cost-utility analysis and modern portfolio theory to inform decision processes in a changing climate. In: 18th World Imacs Congress and Modsim 09 International Congress on Modelling and Simulation, pp. 2385–2391, 1(2).
Pan, D., Wiersma, G., Williams, L., Fong, Y.S., 2013. More than a number: unexpected benefits of return on investment analysis. J. Acad. Libr. 39 (6), 566–572.
Pasini, S., Torresan, S., Rizzi, J., Zabeo, A., Critto, A., Marcomini, A., 2012. Climate change impact assessment in veneto and friuli plain groundwater. Part II: a spatially resolved regional risk assessment. Sci. Total Environ. 440, 219–235.
Pressey, R.L., Cabeza, M., Watts, M.E., Cowling, R.M., Wilson, K.A., 2007. Conservation planning in a changing world. Trends Ecol. Evol. 22 (11), 583–592.
Rakhmatullaev, S., Huneau, F., Kazbekov, J., Le Coustumer, P., Jumanov, J., El Oifi, B., Motelica-Heino, M., Hrkal, Z., 2010. Groundwater resources use and management in the Amu Darya river basin (Central Asia). Environ. Earth Sci. 59 (6), 1183–1193.
Rankovic, V., Drenovak, M., Stojanovic, B., Kalinic, Z., Arsovski, Z., 2014. The mean-value at risk static portfolio optimization using genetic algorithm. Comput. Sci. Inf. Syst. 11 (1), 89–109.
Rejani, R., Jha, M.K., Panda, S.N., Mull, R., 2008. Simulation modeling for efficient groundwater management in Balasore coastal basin, India. Water Resour. Manag. 22 (1), 23–50.
Sekhar, M., Shindekar, M., Tomer, S.K., Goswami, P., 2013. Modeling the vulnerability of an urban groundwater system due to the combined impacts of climate change and management scenarios. Earth Interact. 17.
Shen, D.J., 2015. Groundwater management in China. Water Policy 17 (1), 61–82.
Sophocleous, M., 2009. Review: groundwater management practices, challenges, and innovations in the high Plains aquifer, USA – lessons and recommended actions. Hydrogeol. J. 18 (3), 559–575.
Sun, R., Jin, M., Giordano, M., Villholth, K.G., 2009. Urban and rural groundwater use in Zhengzhou, China: challenges in joint management. Hydrogeol. J. 17 (6), 1495–1506.
Yang, Y., Rubio, F., Scutari, G., Palomar, D.P., 2013. Multi-portfolio optimization: a potential game approach. IEEE T. Signal Proces. 61 (22), 5590–5602.
Zhu, B., 2013. Management strategy of groundwater resources and recovery of over-extraction drawdown funnel in Huaibei city, China. Water Resour. Manag. 27 (9), 3365–3385.