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A simulation-based water-environment management model for regional sustainability in compound wetland ecosystem under multiple uncertainties

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ABSTRACT

In this study, a simulation-based water-environment management model with Laplace scenario analysis (SWML) is developed for planning regional sustainability in compound wetland ecosystem. SWML can not only deal with spatial and temporal variations of hydrologic elements within the watershed, but also handle multiple uncertainties presented in terms of probability, possibility distributions, and fuzzy sets. Meanwhile, policy scenario analysis with Laplace's criterion (PSL) is introduced to handle probability of each scenario occurrence under insufficient data availability. The developed SWML is applied to water-environment management in Xixian wetland (located in north of China), where a compound wetland ecosystem (CWE) would be embedded into the concept of eco-county to remit contradiction between human activity and environmental issue through ecological mechanism. Results of ecological effect, water allocation pattern, pollution mitigation scheme and system benefit under various scenarios are obtained, which can support policymakers adjusting current plan with a cost-effective and sustainable manner. Meanwhile, satisfaction degrees for constraints using necessity levels and Laplace's criterions can support generating a robust plan associated with risk control for regional sustainability in CWE under uncertainties. The findings can support building a new construction of integrated human being–ecological environment system, which is beneficial to achieve integrity of socioeconomic development and eco-environmental sustainability.

1. Introduction

Rapid expansion of human activities, characterized by accelerated industrialization, urbanization and population growth can affect wetland ecosystem by altering land use pattern, biogeochemical and hydrological cycles (You et al., 2014). Adverse effects due to over-stressed development of human beings may result in degenerations even destructions of ecological functions of wetland ecosystem, leading eco-crisis, which is deemed to be one of the most severe issues worldwide today (Bashir et al., 2009; Li et al., 2011). A number of projects for recovering ecological functions and economic values (e.g., flood control, aquifer replenishment, sediment retention, and water filtration) have been advocated, which have produced significant effects on eco-crisis (Mensing et al., 1998). However, numerous individual ecological recovering techniques (e.g., withdrawing cultivation, human activity restriction, ecological compensation mechanism, wetland reserve contribution and adjustment of industry structure) have encountered difficulties to resolve multiple conflicting relationships between human activities and eco-environment protections in the real-world issues (You et al., 2014). Therefore, a compound management system is desired, incorporating multiple manners of ecological recovering techniques and system analysis methods into a general framework, with aim to acquire integrity of socioeconomic development and eco-environmental sustainability.

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Notation

$f_{Laplace}$ system benefit with Laplace criterion (US $)
BM_{tm}, BA_{tn}, BI_{ti}, BP_{tj}, BL_{th}, BE_{tk} net benefit for each water consumption sector (municipality, agriculture, tourism, agricultural processing industry, livestock and compound wetland system) when a volume water being delivered in period t (US $/m^3)
WM_{tm}, WA_{tn}, WI_{ti}, WP_{tj}, WL_{th}, WE_{tk} developing scale target for each water consumption sector in period t (p, ha, p, ton, head, ha)
MWM_{tm}, MWA_{tn}, MWI_{ti}, MWL_{th} maximum developing scale target for each water consumption sector in period t (p, ha, p, ton, head, ha)
mp_{tm}, ra_{tn}, ip_{ti}, pp_{tj}, lp_{th}, re_{tk} the coefficient of water consumption for each water consumer
LM_{tm}, LA_{tn}, LI_{ti}, LP_{tj}, LL_{th}, LE_{tk} loss of water shortage for each water consumption sector when a volume of water not being delivered in period t (US $/p, ha, p, ton, head, ha)
SM_{tm}, SA_{tn}, SI_{ti}, SP_{tj}, SL_{th}, SE_{tk} shortage scale for each water consumption sector in period t (p, ha, p, ton, head, ha)
PNM_{tm}, PNA_{tn}, PNI_{ti}, PNP_{tj}, PNL_{th} the content of TN per volume of waste water for each consumer in period t
PPM_{tm}, PPA_{tn}, PPI_{ti}, PPP_{tj}, PPL_{th} the content of TP per volume of waste water for each consumer in period t
PBM_{tm}, PBA_{tn}, PBI_{ti}, PBP_{tj}, BL_{th} the content of BOD per volume of waste water for each consumer in period t
DM^N_{tm}, DA^N_{tn}, DI^N_{ti}, DP^N_{tj}, DL^N_{th} amount of purified TN discharge by ecological mechanism for each water consumer (ton)
DM^P_{tm}, DA^P_{tn}, DI^P_{ti}, DP^P_{tj}, η^a_i amount of purified TP discharge by ecological mechanism for each water consumer (ton)
DM^B_{tm}, DA^B_{tn}, η^e_i, η^a_i, DL^B_{th} amount of purified BOD discharge by ecological mechanism for each water consumer (ton)
CME_{tm}, CAE_{tn}, CIE_{ti}, CPE_{tj}, CLE_{th} unit benefit of pollution discharge purified by ecological mechanism for each water consumer (US $/ton)
DA^S_{tn} amount of soil intention by ecological mechanism for each water consumer (ton)
MDE^S_{tk} maximum soil intention capacity by ecological mechanism
DA^W_{tn} amount of water conservation by ecological mechanism for each water consumer (ton)
MEA^W_{tk} maximum water conservation capacity by ecological mechanism
WCA_{tn} unit benefit of soil intention by ecological mechanism for each water consumer (US $/ton)
SIA_{tn} unit benefit of water conservation by ecological mechanism for each water consumer (US $/ton)
p_{tp} probability of random water availability QF_{tp} under level p (%) in period t
QF_{tp} water availability from surface water under probability p_{tp} in period t (m^3)
QR_{tp} water flow from river under probability p_{tp} in period t (m^3)
E_{tp} evaporation and infiltration loss of water in period t (m^3)
H_{tp} normal water requirement of watercourse in period t (m^3)
CSM_{tp} maximum water supply capacity in period t (m^3)
NN_t, NP_t, NB_t recycling TN/TP/BOD rate of sewage water from point pollution source by artificial sewage treatment plant
TNP_t, TPP_t, TBP_t allowance TN/TP/BOD discharge in period t (ton)
CM^N_{tm}, CA^N_{tn}, CI^N_{ti}, CP^N_{tj}, CL^N_{th} unit retreatment cost of TN for each water consumer
CM^P_{tm}, CA^P_{tn}, CI^P_{ti}, CP^P_{tj}, CL^P_{th} unit retreatment cost of TP for each water consumer
CM^B_{tm}, CA^B_{tn}, CI^B_{ti}, CP^B_{tj}, CL^B_{th} unit retreatment cost of BOD for each water consumer

Subscript
m municipal sector: m = 1 resident (person), m = 2 municipal services (ha)
n agriculture sector: n = 1 wheat (ha), n = 2 cotton (ha), n = 3 oil plant (ha), n = 4 vegetable (ha)
i tourism sector: i = 1 tourist (person)
h livestock sector: h = 1 pig (head); h = 2 cattle (head); h = 3 poultry (head)
j agricultural processing industry sector: j = 1 farming industry (ton); j = 2 animal husbandry and processing industry (ton)
k ecological sector: k = 1 wetland (ha), k = 2 ecological park (ha), k = 3 forest (ha)
p water level: p = 1 low, p = 2 low-medium, p = 3 medium, p = 4 medium-high, p = 5 high
t planning period: t = 1 period 1, t = 2 period 2, t = 3 period 3

Previously, many research works were conducted to plan the human activity and natural ecosystem through balancing the conflicts between anthropogenic modification and wetland ecosystems protection (Mensing et al., 1998; Johsta et al., 2002; Altunkaynak and Sen, 2007; Vidal-Legaz et al., 2013; Dong et al., 2015; You et al., 2014; Li et al., 2015; Tan et al., 2015). For instance, Johsta et al. (2002) developed an eco-compensation model to determinate the efficiencies of current compensation payments quantitatively for wetland protection policies. Altunkaynak and Sen (2007) introduced fuzzy membership functions to evaluate the dynamic valuation of ecosystem services in the Lake Van, eastern Turkey. Vidal-Legaz et al. (2013) built a dynamic simulation model to calculate the trade-offs between the provisions of two ecosystem services, landscape esthetic value and water supply for human use and the economic development associated with different land use changes. Zeng et al. (2015) developed a fuzzy-quadratic model to plan regional sustainability of floodplain ecosystem under uncertainties, where wetland expansion policies can be analyzed. Among them, water deemed as an effective linkage between anthropogenic activity and environmental conservation can facilitate decision makers adjusting current plans with efficient manners; meanwhile, pollutant discharges in proportion to water consumption would have influenced environment as crucial. Under these situations, an integrated water-environment management system can be built for planning regional sustainability in compound wetland ecosystem (CWE). Nevertheless, a variety of external uncertainties (e.g., random of water availability, vague ecological mechanism, varied ecological components, dubious diffusion and migration process of pollution) would exist in a CWE, incorporating artificial indeterminacies (e.g., imprecision of economic data, adjustment of natural polices and risk preference of policymaker), all of which would enhance the