Reference Number: hess-2024-399-RC2

RESPONSES TO REVIEWER ONE'S COMMENTS

We would like to express our sincere gratitude for your detailed and constructive comments on our manuscript. The comments are valuable and helpful for us to improve the quality of the manuscript. All the concerns raised have been carefully treated and an itemized reply to the reviewer's comments is presented in the revision files.

Point #1

COMMENT: *While the methodology employed in the manuscript effectively addresses the issue of identifying the SHE nexus across multiple temporal and spatial scales, it is important to elaborate on the advantages of the chosen approach in the methodology or introduction section, rather than merely stating its ability to solve the problem.*

RESPONSE: We sincerely appreciate the reviewer's valuable comment regarding the need to elaborate on methodological advantages. We fully concur that explicitly articulating the strengths of our chosen analytical framework in the methodology/introduction sections will better contextualize our approach for readers. In the revised manuscript, we will expand upon some key advantages of our methodology in addressing the impacts of IWDPs across the multiple temporal and spatial scales on the dynamic SHE nexus. The Variable Infiltration Capacity (VIC) hydrological model offers significant advantages in multiple temporal and spatial scale runoff simulation. It has flexible spatial resolution, making it suitable for hydrological modeling at scales ranging from small catchments to large basins, with minimal loss of accuracy. VIC model can simulate hydrological processes at various time scales, from hourly to annual, catering to different research needs. The VIC model also efficiently uses gridded data, making it highly adaptable for large-scale regional or global studies, and supports a wide range of input data types. The Modified Tennant Method Based on Multilevel Habitat Conditions method builds upon the Tennant method, modifying it based on three parameters: average periodic flow, water period, and percentage (Li and Kang, 2014). It can solve four key problems existed in the current ecological flow standards: spatial transferability, monthly variability, inter-annual variability and scalability (Li, et al., 2015). This modification helps mitigate the impacts of extreme inter-annual flow variations and uneven intra-annual distribution. The Log Response Ratio method captures non-linear feedback loops within complex SHE nexus systems. And our scenarios architecture enables systematic exploration of SHE nexus systems by combining different clusters of IWDPs and the priority orders of S, H, and E, offering flexibility in modeling system behavior under different conditions.

The revised and relevant parts are:

> "To simulate runoff results at multiple temporal and spatial scales, the Variable Infiltration Capacity (VIC) hydrological model is selected. The Variable Infiltration Capacity (VIC) hydrological model offers significant advantages in multiple temporal and spatial scale runoff simulation. It is a large-scale distributed hydrological model based on the spatial distribution grid of Soil Vegetation Atmospheric Transfer Schemes (SVATS) (Liang, et al., 1994), making it highly adaptable to studies at different spatial scales and supporting a wide range of input data types. The VIC model can simulate hydrological processes at various time scales, from hourly to annual, catering to different research needs. It excelled at simulating both the energy balance and water balance between the land and atmosphere, thereby addressing the oversight of energy processes in traditional hydrological models. The VIC model has been widely applied in runoff simulations across various basins worldwide, consistently yielding outstanding results. There are five steps to construct a VIC model (Koohi et al., 2022): ① collect and organize data; ② preprocesses of the VIC model; ③ construct VIC model of the selected basin; ④ run the catchment module; ⑤ parameter calibration and validation. During the calibration process, important parameters highlighted in Table 1 are automatically calibrated using MATLAB to achieve the optimal parameter combination."(**On page 4 of the revised manuscript**)
>
> "In order to establish a multi-level ecological flow standard to aid in evaluating river ecological health, the multi-level ecological flows are estimate by the MTMMHC method. There are over 200 methods for EFs estimation worldwide, typically categorized into four types: hydrological, hydraulic, habitat simulation, and holistic methods (Tharme, 2003). The Tennant method, which determines EFs based on predetermined percentages of average annual flow, is the most widely used

hydrological method (Tharme, 2003). The MTMMHC method (Li and Kang, 2014) modifies the Tennant method based on three parameters: average periodic flow, water period, and percentage. It can solve four key problems existed in the current ecological flow standards: spatial transferability, monthly variability, inter-annual variability and scalability (Li, et al., 2015). Indeed, the MTMMHC method can avoid the impacts of extreme inter-annual flow events and uneven intra-annual distribution. This enables the calculation of different guarantee rates for various river sections, water years (e.g., wet, normal, and dry years), and months. It reflects the temporal and spatial variability of EFs, and provides a comprehensive and reasonable multi-level ecological flows standards. The steps of the MTMMHC method are as follows." (**On page 6 of the revised manuscript**)

"To analyse the feedback loops in Nexus I, Nexus II and Nexus III in Figure 1, the log response ratio (*LRR*) quantization method (Patrick et al., 2022) is used to quantify the responses of S, H, and E with different clusters of IWDPs. This method captures non-linear feedback loops within complex SHE nexus systems." (**On page 9 of the revised manuscript**)

"To identify the impacts of different clusters of IWDPs on the SHE nexus, scenarios are set according to the following three aspects: with or without IWDPs (i.e., two types for IWDPs), different clusters of IWDPs (i.e., four clusters for the above two types), and the priority orders of S, H, and E. As there are three components for the highest priority, six scenarios can be obtained through the combination of the three components. As all S, H, and E are determined from standard scheduling rules, there are also three types for the standard scheduling rules. Combined with the types of different clusters of IWDPs, there will be a total of 30 scenarios (i.e., 4 clusters of IWDPs × 6 types for the highest priority combinations +2 types for IWDPs × 3 types for standard scheduling rules) as listed in Table 2. Specifically, to iteratively set the priority orders of S, H, and E, all three components are all in standard scheduling rules firstly. Secondly, the highest priority is set to water supply (as denoated by S-Priority), with the regional water supply increased to 120 %. And thirdly, hydropower generation (H-Priority) is prioritized to achieve the maximum output during the planned period. Finally, environmental conservation (E-Priority) is addressed through ensuring that the reservoir outflow meets $OEF_{xy(\max)}$. These scenarios offer flexibility in modeling SHE nexus system behavior under different conditions.” (**On page 10 of the revised manuscript**)

Point #2

COMMENT: *The elements presented in Figure 4 are insufficient to clearly illustrate the geographical characteristics of the study area. Additionally, it is necessary to label the names of various hydrological stations and reservoirs on the map, so that readers can more easily interpret the information. The clarity of Figure 6 should be improved, and the color scheme used to differentiate observed and simulated data needs to be adjusted for better distinction. Furthermore, the title of Figure 6 could be simplified for conciseness.*

RESPONSE: We are very thankful for the reviewer’s insightful comment and valuable reminder. We have revised Figure 4 to enhance the geographical characteristics of Hanjiang River Basin (HRB) by adding elements such as topography and rivers to make the map clearer. We have also labeled the hydrological stations and reservoirs on the map, ensuring that readers can easily identify these key locations. To eliminate readers' disputes over the territories in the map, we have made modifications to Figure 4 using the map with the examination approval number GS (2024) No.0650. Regarding Figure 6, we have improved its clarity by ensuring that text, line thickness, and other elements are sharp and legible. Additionally, we have adjusted the color scheme used to differentiate observed and simulated data, opting for more contrasting colors that are easily distinguishable, and have ensured the legend clearly indicates which color corresponds to each dataset. Lastly, we have simplified the title of Figure 6 to a more concise. The revised and relevant parts are:

"

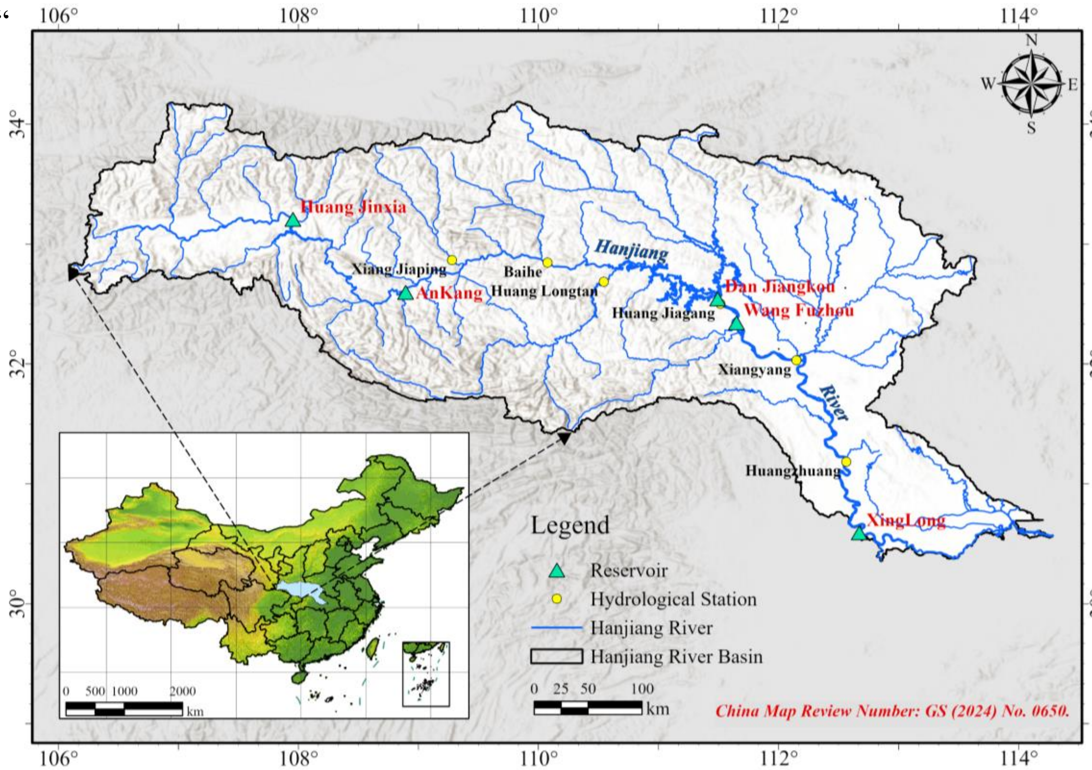

Figure 4. Overview map of the study area.

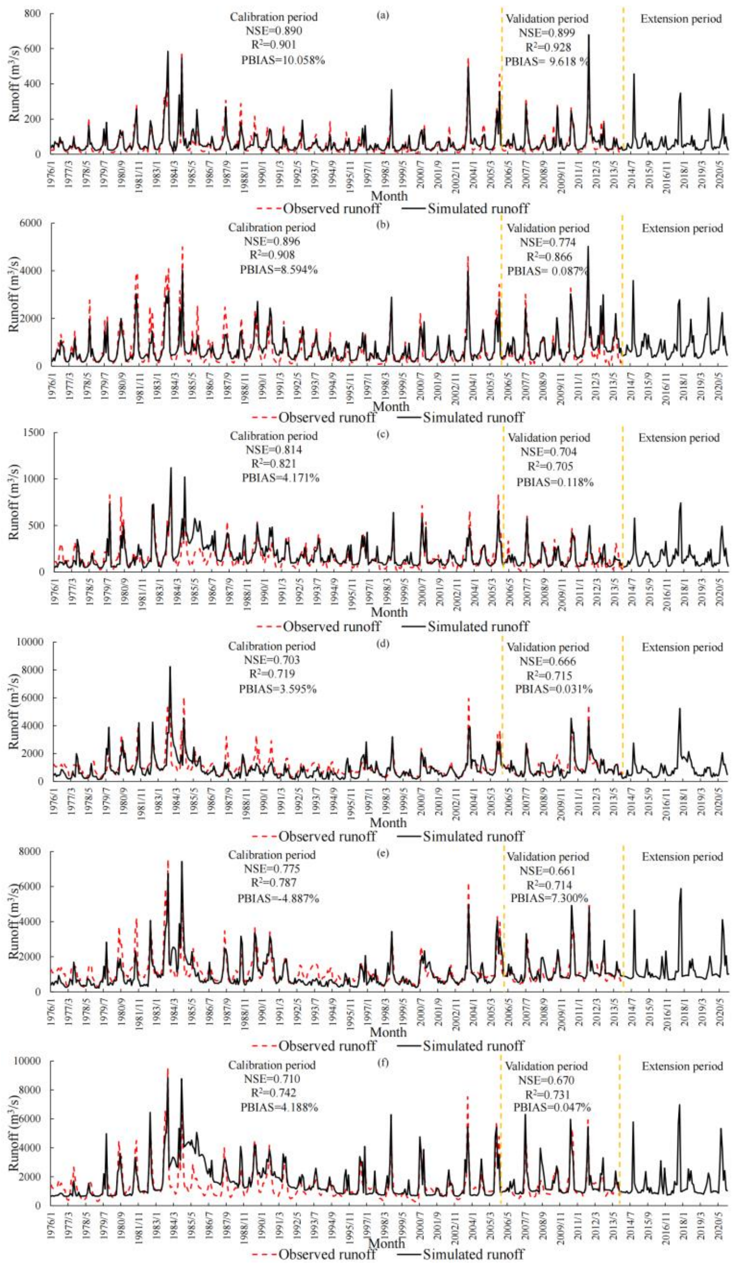

Figure 6. Calibration and validation results of simulation at hydrological stations: (a)Xiangjiangping, (b) Baihe, (c) Huanglongtan, (d) Huangjiagang, (e) Xiangyang, (f) Huangzhuang."

Point #3

COMMENT: *Is the framework proposed in the manuscript broadly applicable? It might be helpful for the manuscript to provide a clearer explanation of the framework and further clarify* *the scope of applicability of the proposed method.*

RESPONSE: We greatly appreciate the reviewer's insightful comments. This framework offers a systematic and quantitative approach to examining the spatiotemporal variations of SHE nexus with external perturbations. It elucidates the existence and nature of collaborative states among S, H, and E. All the methods in the framework, such as the VIC model, the Modified Tennant Method Based on Multilevel Habitat Conditions, and the Log Response Ratio method, are not region-specific and can be applied to the study of SHE nexus in different basins worldwide. Therefore, the proposed framework can be applied globally to identify the feedbacks of the SHE nexus in basins with inter-basin water diversion projects. The applicability of the framework is clearly explained in the paper. The corresponding part is:

> "To address the impacts of IWDPs across the multiple temporal and spatial scales on the dynamic SHE nexus, multiple temporal and spatial scales runoffs from the water donating basins are provided through a distributed hydrological model. And multi-level ecological flows and their corresponding multi-level ecological flow standards are also determined according to an available method with spatial-temporal variability. To facilitate the identification of the impacts of IWDPs on SHE nexus, scenario experiments are set by "with/without IWDPs". In order to take the different clusters of IWDPs into account, scenario experiments are classified by the impacts of IWDPs on water donation area, on water receiving area or on an area with both water donation and water receiving if there are IWDPs. To evaluate the feedback loops of the SHE nexus, the priority order of S, H, and E are iteratively set in all reservoir nodes. We set different types of the highest priority in S, H, and E (i.e., S-Priority, H-Priority, and E-Priority) and take the standard scheduling rules as reference scenarios. All scenarios are modeled in a multisource input-output reservoir generalization model, and differences between scenarios are quantified with a response ratio indicator. And the feedback loops with the different impacts of IWDPs are identified through a response ratio indicator. To explore the collaborative states, positive mutation in a response ratio across time-space is found between pairwise components of SHE. This framework can be applied globally to identify the feedbacks of the SHE nexus in basins with IWDPs. Thus, our research framework is illustrated as Figure 1." (**On page 3 of the revised manuscript**)

Point #4

COMMENT: *The manuscript offers limited description of the baseline scenarios. This section could be expanded to clarify the rationale behind the selection of the baseline scenarios, enabling readers to better understand the results.*

RESPONSE: We are very thankful for the reviewer's insightful comments and helpful suggestions. We have provided a more detailed description of the baseline scenarios and added explanations of the scenarios in the figure captions.

The revised parts are:

"To analyse the feedback loops of SHE nexus without IWDPs, the differences between the $S_{1-0-p-c}$ and $S_{1-0-4-c}$ scenarios are determined (i.e., the feedback loops of Nexus I as shown in Figure 1.). To analyse the feedback loops with IWDPs (i.e., the feedback loops of Nexus II as shown in Figure 1.), the differences between the $S_{2-3-p-c}$ and $S_{2-3-4-c}$ scenarios are determined. Thus, the differences between Nexus I and Nexus II can figure out the impacts of IWDPs on the SHE nexus. To identify the SHE nexus with different clusters of IWDPs (i.e., the feedback loops of Nexus III as shown in Figure 1.), the differences between $S_{2-m-p-c}$ and $S_{1-0-4-c}$ scenarios are determined. Thus, the differences between Nexus I and Nexus III can figure out the impacts of different IWDP clusters on the SHE nexus. $S_{1-0-4-c}$ (i.e., the scenarios with standard scheduling rules without IWDPs) and $S_{2-3-4-c}$ (i.e., the scenarios with standard scheduling rules with IWDPs), are the baseline scenarios for distinguishing Nexus I, Nexus III, and Nexus II. In the same way, to clarify the impacts of IWDPs on the three components, the differences between the $S_{1-0-4-c}$ and $S_{2-3-4-c}$ scenarios are determined." (**On page 10 of the revised manuscript**)

"

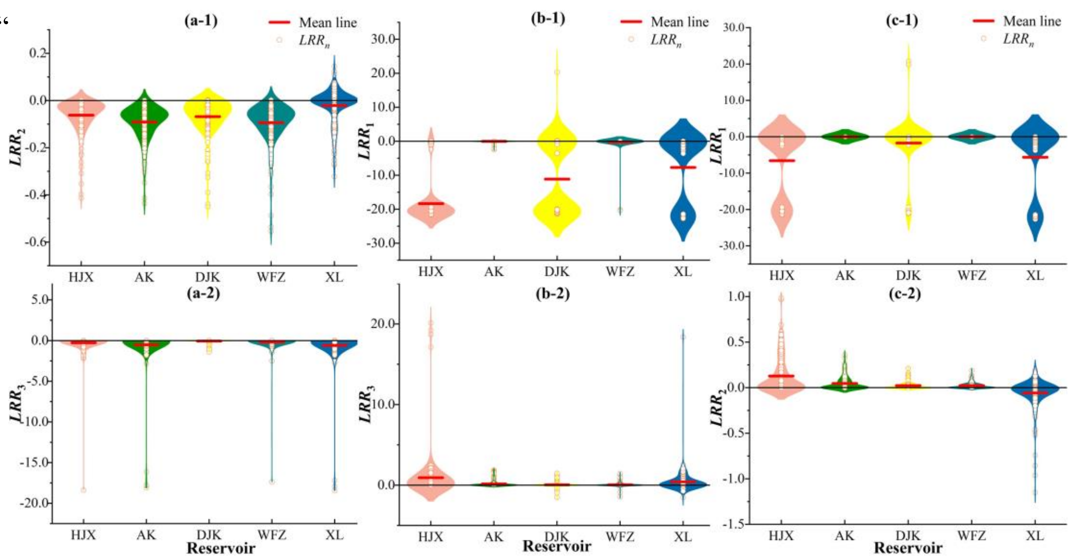

Figure 7. the differences of indexes (i.e., *LRR_1*, *LRR_2*, *LRR_3* for log response ratio of the S, H, and E component) without IWDPs (i.e., between $S_{1-0-p-c}$ and $S_{1-0-4-c}$) at the monthly scale: (a-1) are *LRR_2* with the highest priority in S (i.e., between $S_{1-0-1-1}$ and $S_{1-0-4-2}$), (a-2) are *LRR_3* with the highest priority in S (i.e., between $S_{1-0-1-2}$ and $S_{1-0-4-3}$), (b-1) are *LRR_1* with the highest priority in H (i.e., between $S_{1-0-2-1}$ and $S_{1-0-4-1}$), (b-2) are *LRR_3* with the highest priority in H (i.e., between $S_{1-0-2-2}$ and

$S_{1-0-4-3}$), (c-1) are LRR_1 with the highest priority in E (i.e., between $S_{1-0-3-1}$ and $S_{1-0-4-1}$), (c-2) are LRR_2 with the highest priority in E (i.e., between $S_{1-0-3-2}$ and $S_{1-0-4-2}$).

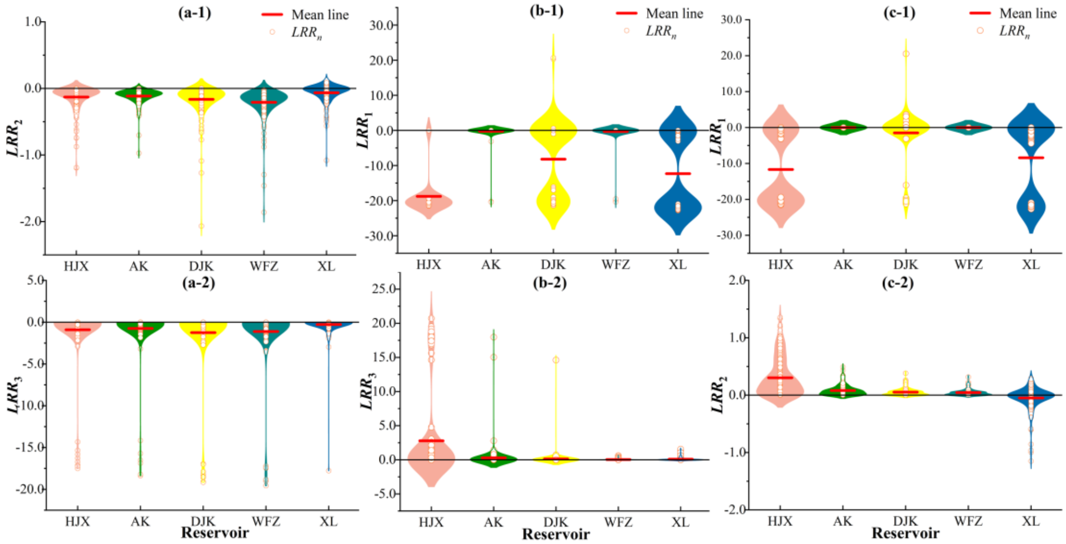

Figure 8. the differences of indexes (i.e., LRR_1, LRR_2, LRR_3 for log response ratio of the S, H, and E component) with IWDPs (i.e., between $S_{2-3-p-c}$ and $S_{2-3-4-c}$) at the monthly scale: (a-1) are LRR_2 with the highest priority in S (i.e., between $S_{2-3-1-1}$ and $S_{2-3-4-2}$), (a-2) are LRR_3 with the highest priority in S (i.e., between $S_{2-3-1-2}$ and $S_{2-3-4-3}$), (b-1) are LRR_1 with the highest priority in H (i.e., between $S_{2-3-2-1}$ and $S_{2-3-4-1}$), (b-2) are LRR_3 with the highest priority in H (i.e., between $S_{2-3-2-2}$ and $S_{2-3-4-3}$), (c-1) are LRR_1 with the highest priority in E (i.e., between $S_{2-3-3-1}$ and $S_{2-3-4-1}$), (c-2) are LRR_2 with the highest priority in E (i.e., between $S_{2-3-3-2}$ and $S_{2-3-4-2}$).

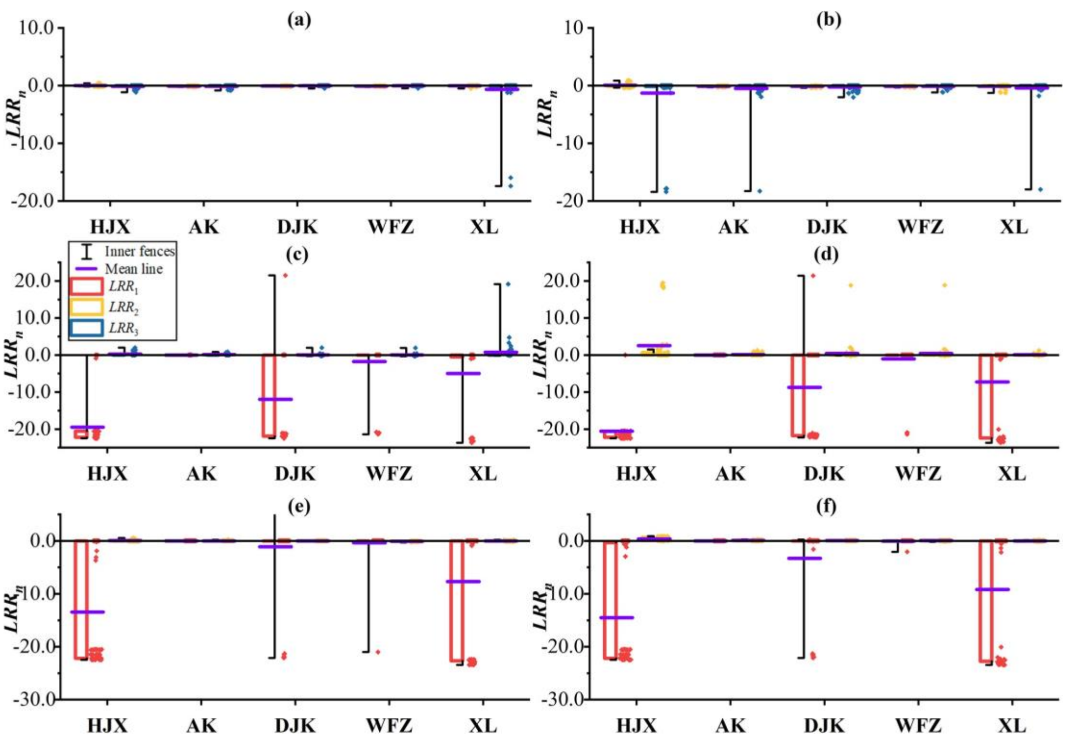

Figure 9. LRR_n with different highest priorities (i.e., between $S_{w-m-1-c}$ and $S_{w-m-4-c}$) at the seasonal scale: (a) and (b) are LRR_n with the highest priority in S without IWDPs (i.e., between $S_{1-0-1-c}$ and $S_{1-0-4-c}$) and with IWDPs (i.e., between $S_{2-3-1-c}$ and $S_{2-3-4-c}$), (c) and (d) are LRR_n with the highest priority in H without IWDPs (i.e., between $S_{1-0-2-c}$ and $S_{1-0-4-c}$) and with IWDPs (i.e., between $S_{2-3-2-c}$ and $S_{2-3-4-c}$). (e) and (f) are LRR_n with the highest priority in E without IWDPs (i.e., between $S_{1-0-3-c}$ and

$S_{1\text{-}0\text{-}4\text{-}c}$) and with IWDPs (i.e., between $S_{2\text{-}3\text{-}3\text{-}c}$ and $S_{2\text{-}3\text{-}4\text{-}c}$).

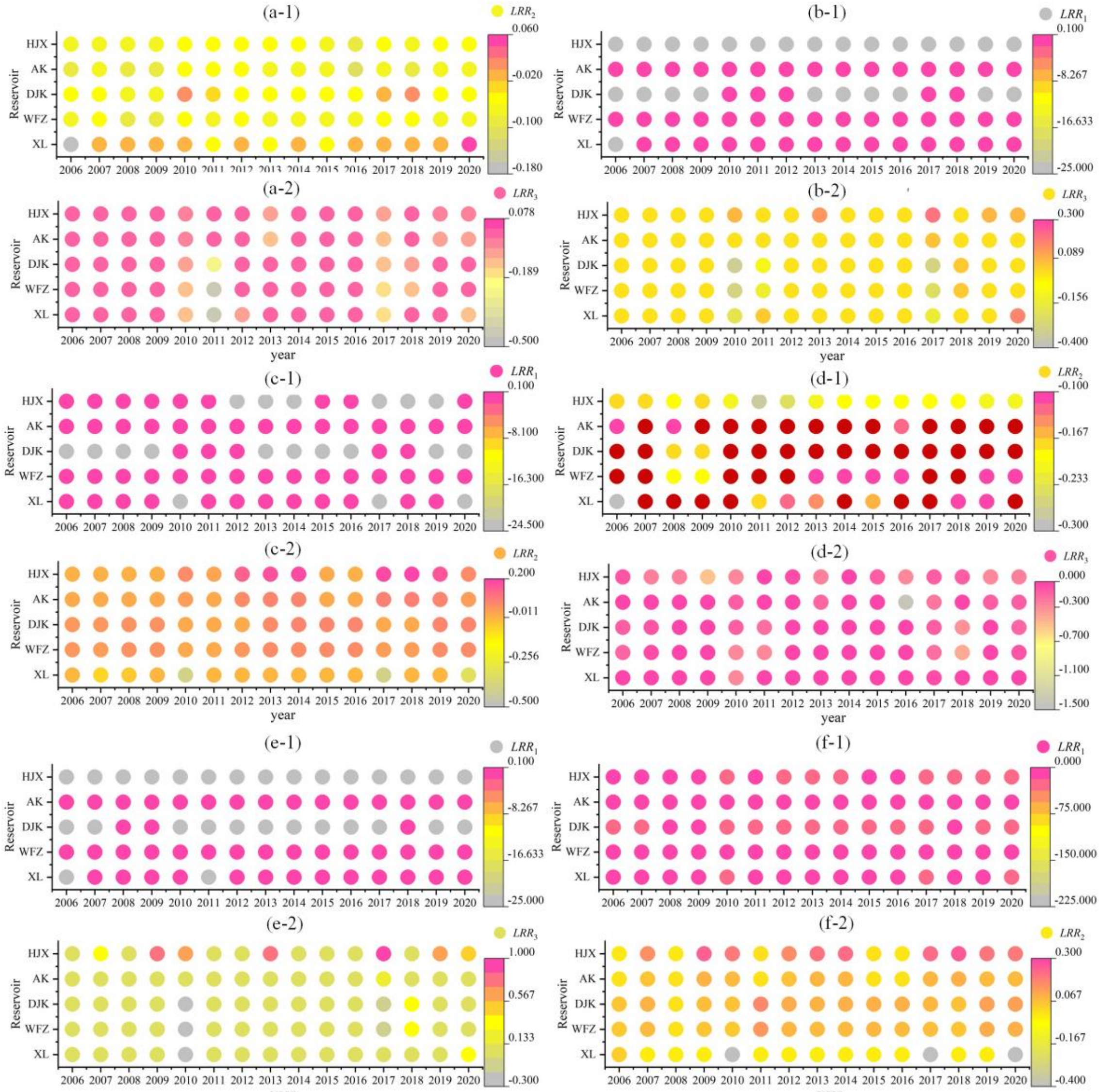

Figure 10. *LRRn* without and with IWDPs at annual scale: (a-1) and (a-2) are *LRR*2 and *LRR*3 with the highest priority in S without IWDPs (i.e., between $S_{1\text{-}0\text{-}1\text{-}c}$ and $S_{1\text{-}0\text{-}4\text{-}c}$), (b-1) and (b-2) *LRR*1 and *LRR*3 with the highest priority in H without IWDPs (i.e., between $S_{1\text{-}0\text{-}2\text{-}c}$ and $S_{1\text{-}0\text{-}4\text{-}c}$), (c-1) and (c-2) are *LRR*1 and *LRR*2 with the highest priority in E without IWDPs (i.e., between $S_{1\text{-}0\text{-}3\text{-}c}$ and $S_{1\text{-}0\text{-}4\text{-}c}$), (d-1) and (d-2) *LRR*2 and *LRR*3 with the highest priority in S with IWDPs (i.e., between $S_{2\text{-}3\text{-}1\text{-}c}$ and $S_{2\text{-}3\text{-}4\text{-}c}$), (e-1) and (e-2) are *LRR*1 and *LRR*3 with the highest priority in H with IWDPs(i.e., between $S_{2\text{-}3\text{-}2\text{-}c}$ and $S_{2\text{-}3\text{-}4\text{-}c}$), (f-1) and (f-2) *LRR*1 and *LRR*2 with the highest priority in E with IWDPs(i.e., between $S_{2\text{-}3\text{-}3\text{-}c}$ and $S_{2\text{-}3\text{-}4\text{-}c}$).

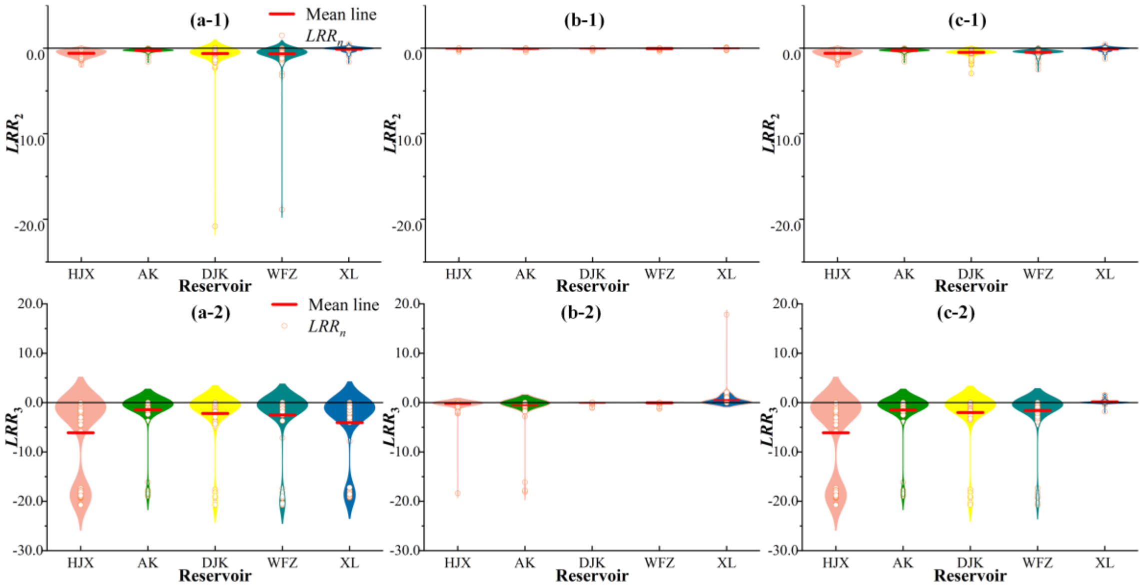

Figure 11. ***LRR_n*** **values when there are different clusters of IWDPs and S-Priority was set at the monthly scale: (a-1) and (a-2) are *LRR_2* and *LRR_3* when there is only water donation (i.e., between $S_{2\text{-}1\text{-}1\text{-}c}$ and $S_{1\text{-}0\text{-}4\text{-}c}$), (b-1) and (b-2) are *$LRR_2$* and *$LRR_3$* when there is only water receiving (i.e., between $S_{2\text{-}2\text{-}1\text{-}c}$ and $S_{1\text{-}0\text{-}4\text{-}c}$), (c-1) and (c-2) are *$LRR_2$* and *$LRR_3$* when there are both donation and receiving (i.e., between $S_{2\text{-}3\text{-}1\text{-}c}$ and $S_{1\text{-}0\text{-}4\text{-}c}$).**

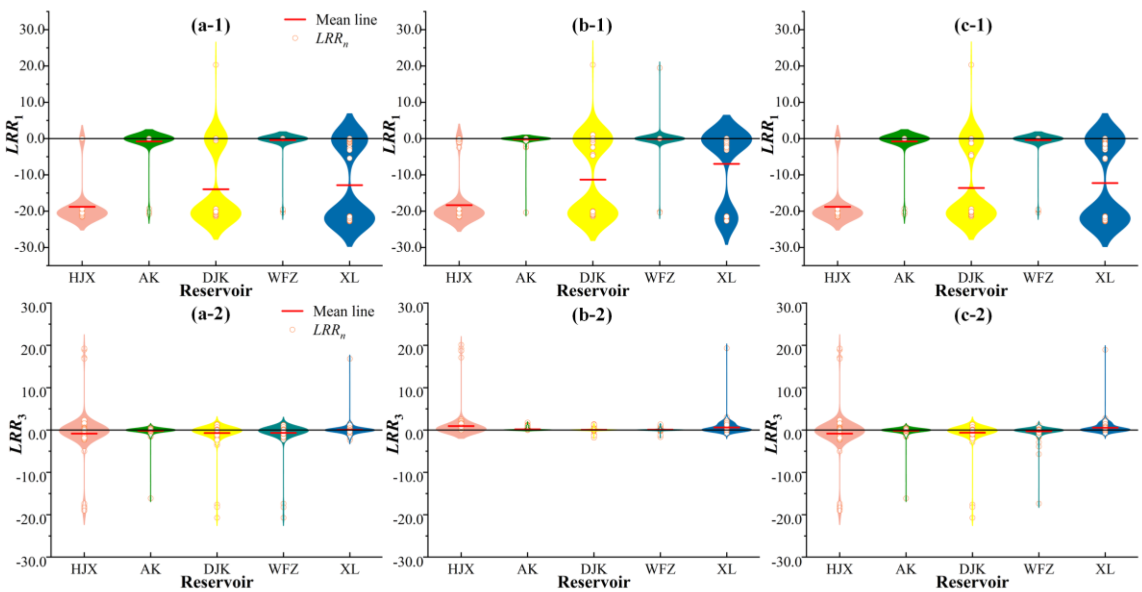

Figure 12. ***LRR_n*** **values when there are different clusters of IWDPs and H-Priority was set at the monthly scale: (a-1) and (a-2) are *LRR_2* and *LRR_3* when there is only water donation (i.e., between $S_{2\text{-}1\text{-}2\text{-}c}$ and $S_{1\text{-}0\text{-}4\text{-}c}$), (b-1) and (b-2) are *$LRR_2$* and *$LRR_3$* when there is only water receiving (i.e., between $S_{2\text{-}2\text{-}2\text{-}c}$ and $S_{1\text{-}0\text{-}4\text{-}c}$), (c-1) and (c-2) are *$LRR_2$* and *$LRR_3$* when there are both donation and receiving(i.e., between $S_{2\text{-}3\text{-}2\text{-}c}$ and $S_{1\text{-}0\text{-}4\text{-}c}$).**

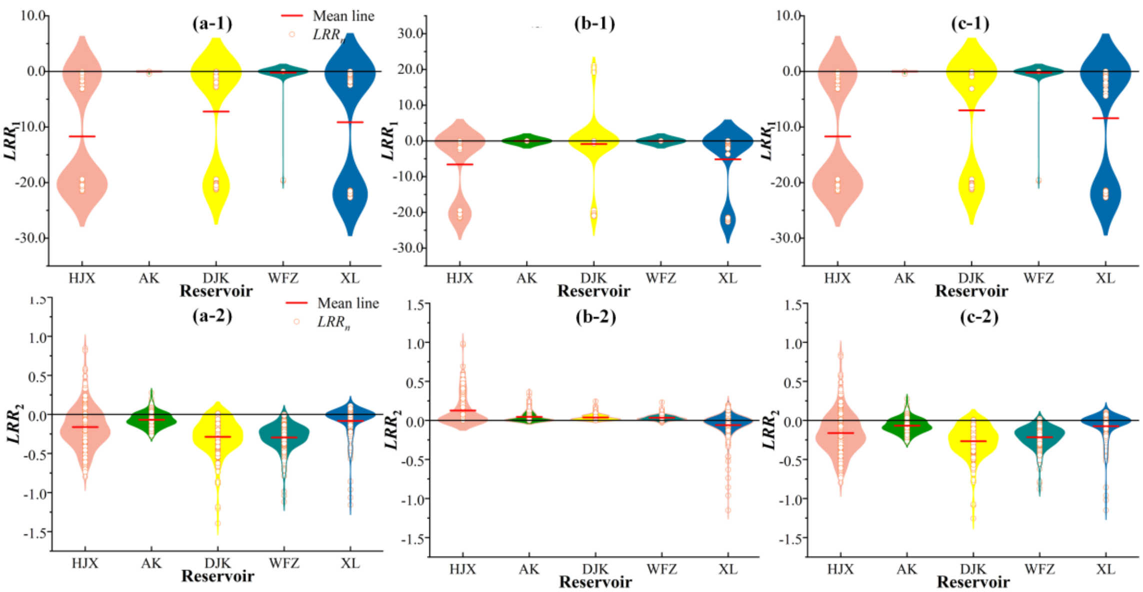

Figure 13. ***LRR_n*** **values when there are different clusters of IWDPs and E-Priority was set at the monthly scale: (a-1) and (a-2) are *LRR_1* and *LRR_2* when there is only water donation (i.e., between $S_{2-1-3-c}$ and $S_{1-0-4-c}$), (b-1) and (b-2) are *LRR_1* and *LRR_2* when there is only water receiving (i.e., between $S_{2-2-3-c}$ and $S_{1-0-4-c}$), (c-1) and (c-2) are *LRR_1* and *LRR_2* when there are both donation and receiving (i.e., between $S_{2-3-3-c}$ and $S_{1-0-4-c}$).**

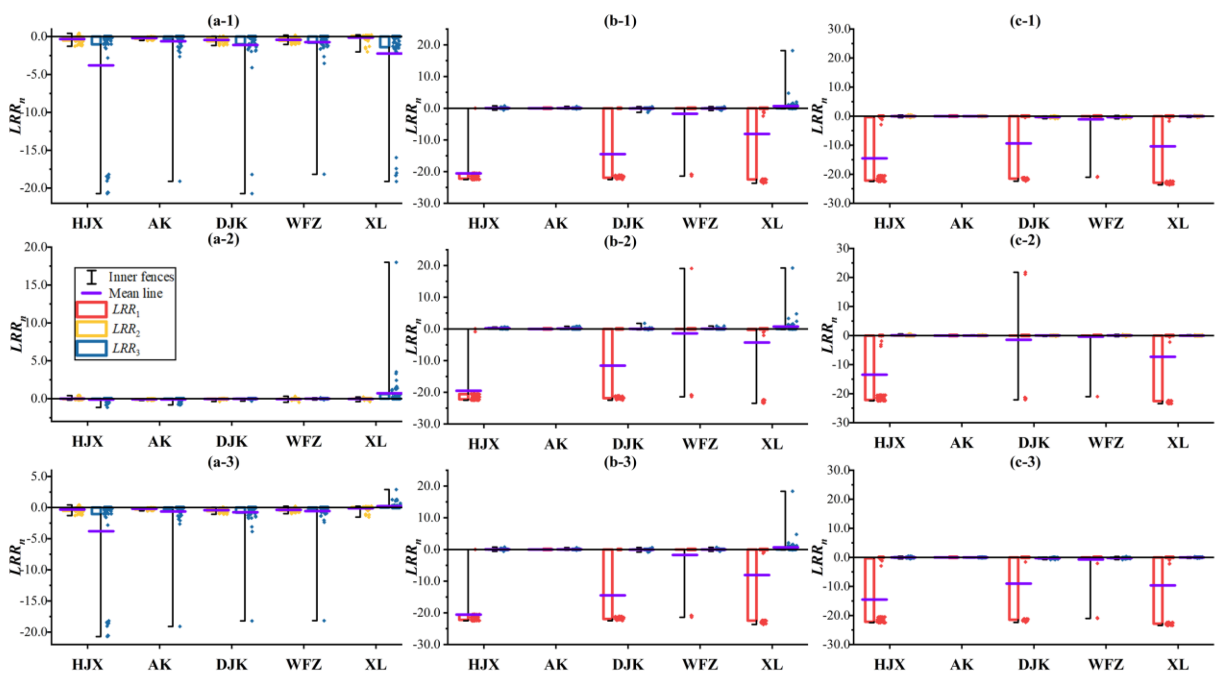

Figure 14. ***LRR_n*** **values when there are different clusters of IWDPs at the seasonal scale: (a-1), (a-2) and (a-3) are *LRR_n* when there was only water donation, when there was only water receiving, when there were both donation and receiving and S-Priority was set (i.e., between $S_{2-m-1-c}$ and $S_{1-0-4-c}$); (b-1), (b-2) and (b-3) are those when H-Priority was set (i.e., between $S_{2-m-2-c}$ and $S_{1-0-4-c}$); (c-1), (c-2) and (c-3) are those when E-Priority was set (i.e., between $S_{2-m-3-c}$ and $S_{1-0-4-c}$).**

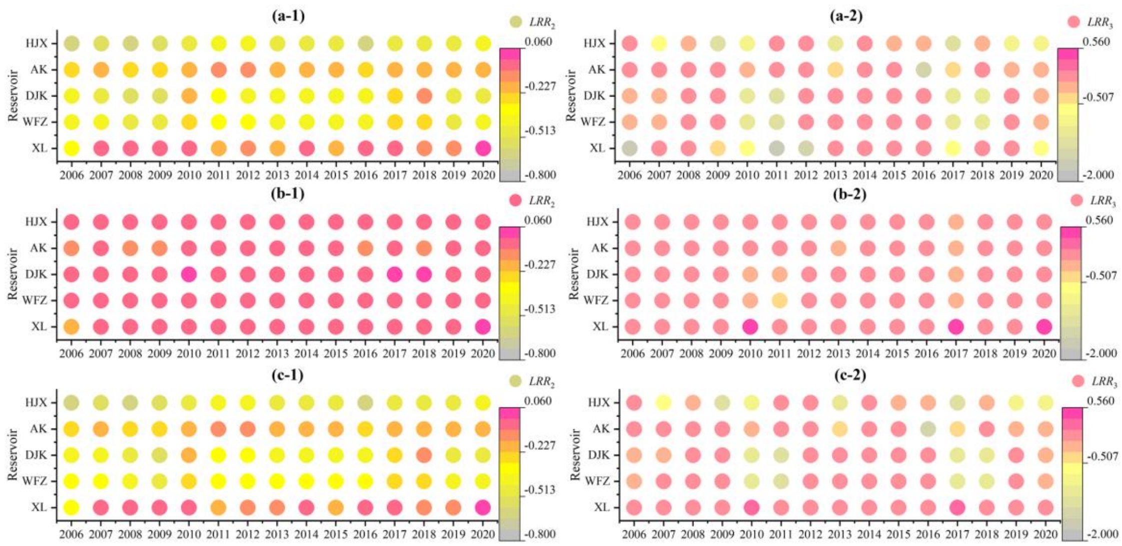

Figure 15. ***LRR_n*** **values when there are different clusters of IWDPs and S-Priority was set at the annual scale: (a-1) and (a-2) are** ***LRR_2*** **and** ***LRR_3*** **when there was only water donation (i.e., between $S_{2-1-1-c}$ and $S_{1-0-4-c}$), (b-1) and (b-2) are those when there was only water receiving (i.e., between $S_{2-2-1-c}$ and $S_{1-0-4-c}$), (c-1) and (c-2) are those when there were both donation and receiving (i.e., between $S_{2-3-1-c}$ and $S_{1-0-4-c}$).**

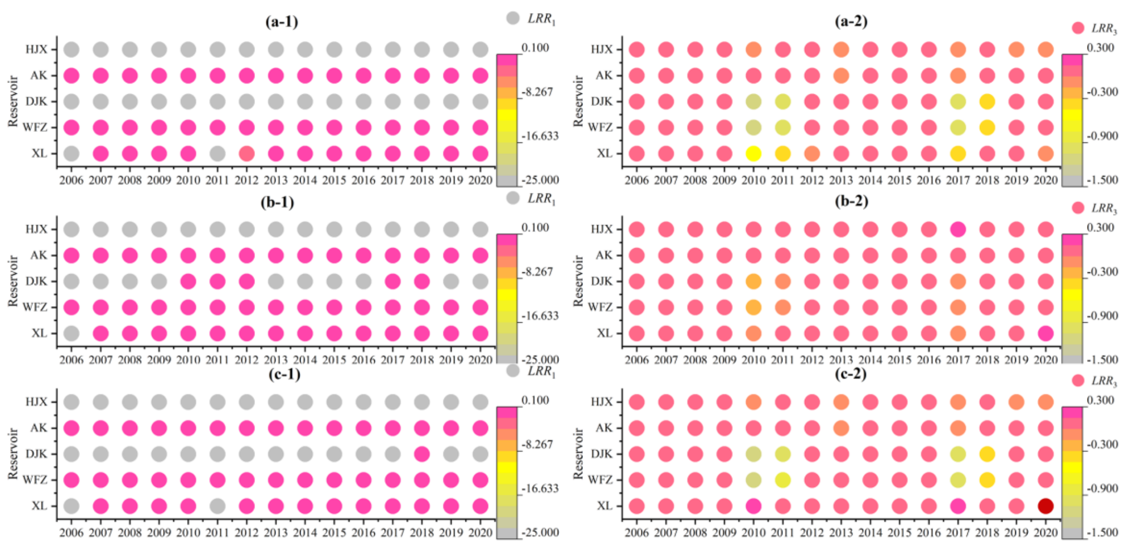

Figure 16. ***LRR_n*** **values when there are different clusters of IWDPs and H-Priority was set at the annual scale: (a-1) and (a-2) are** ***LRR_2*** **and** ***LRR_3*** **when there was only water donation (i.e., between $S_{2-1-2-c}$ and $S_{1-0-4-c}$), (b-1) and (b-2) are those when there was only water receiving (i.e., between $S_{2-2-2-c}$ and $S_{1-0-4-c}$), (c-1) and (c-2) are those when there were both donation and receiving (i.e., between $S_{2-3-2-c}$ and $S_{1-0-4-c}$).**

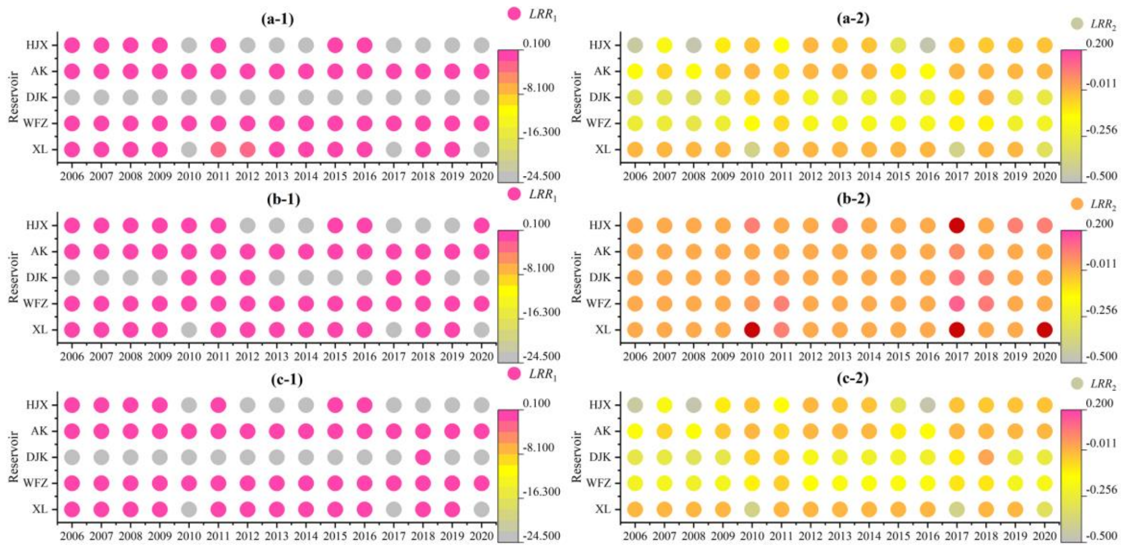

Figure 17. *LRR_n* values when there are different clusters of IWDPs and E-Priority was set at the annual scale: (a-1) and (a-2) are *LRR*2 and *LRR*3 when there was only water donation (i.e., between $S_{2\text{-}1\text{-}3\text{-}c}$ and $S_{1\text{-}0\text{-}4\text{-}c}$), (b-1) and (b-2) are those when there was only water receiving (i.e., between $S_{2\text{-}2\text{-}3\text{-}c}$ and $S_{1\text{-}0\text{-}4\text{-}c}$), (c-1) and (c-2) are those when there were both donation and receiving (i.e., between $S_{2\text{-}3\text{-}3\text{-}c}$ and $S_{1\text{-}0\text{-}4\text{-}c}$).

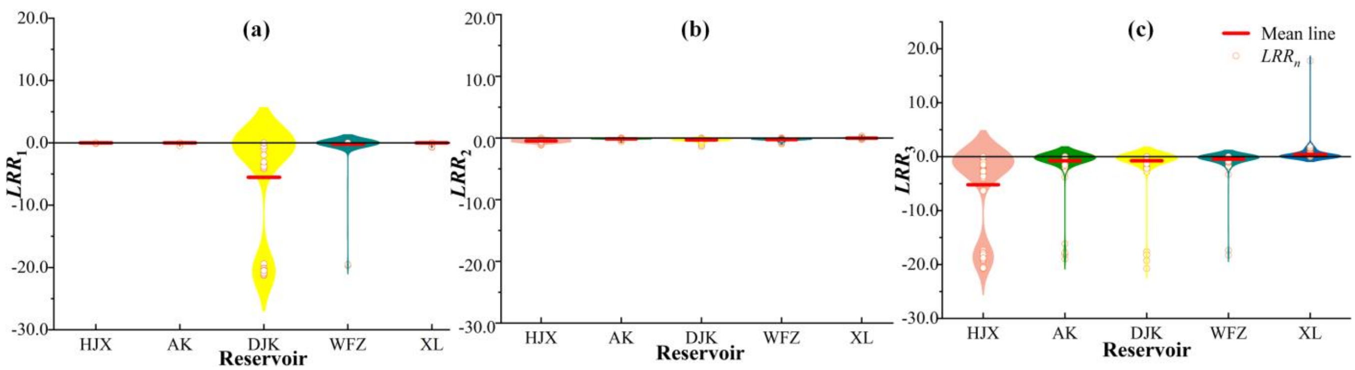

Figure 18. the differences of indexes (i.e., (a) *LRR*1, (b) *LRR*2, (c) *LRR*3 for log response ratio of the S, H, and E component) between $S_{2\text{-}3\text{-}4\text{-}c}$ and $S_{1\text{-}0\text{-}4\text{-}c}$ at the monthly scale.”

Point #5

COMMENT: *The results and discussion section is too long, please make it more concise and highlight the key results.*

RESPONSE: We agree that the section could be more concise and focused on the key findings. In response to this comment, we have increased the analysis of the results and reduced the repetition of the results in the charts. And we have refined the analysis and discussion of similar results at different scales, remove repetitive expressions, and emphasize the differences in results caused by different spatial and temporal scales. We believe these changes have made the Results and Discussion section more concise while maintaining the scientific rigor and clarity of our findings. The revised parts are:

“4 Results and Discussion

4.1 Calibration and verification of VIC model

The HRB was discretized into 2103 grids of 5-arc minutes. Inputting meteorological forcing, soil parameter, and vegetation parameter data for each grid, runoffs were simulated. Model warm-up was spanned 1972-1975, while its calibration was conducted from 1976 to 2005, and the validation was from 2006 to 2013. And runoff from 2014 to 2020 was extension simulated for its post-validation. All the results are shown in Figure 6. It can be found that the accuracies of the simulations at all hydrological stations are acceptable, and the superior performances were found in upstream. For instance, *NSE* for calibration and validation were 0.896 and 0.774, with corresponding R^2 of 0.908 and 0.866 at BH. Due to the intense human activity impacts in mid–lower reaches of the HRB, the poorer performance were found at HJG while their *NSE* values still exceed 0.600. *PBIAS* for all these six stations during calibration and validation periods ranged within [-5 %，11 %], which also indicates satisfactory agreement.

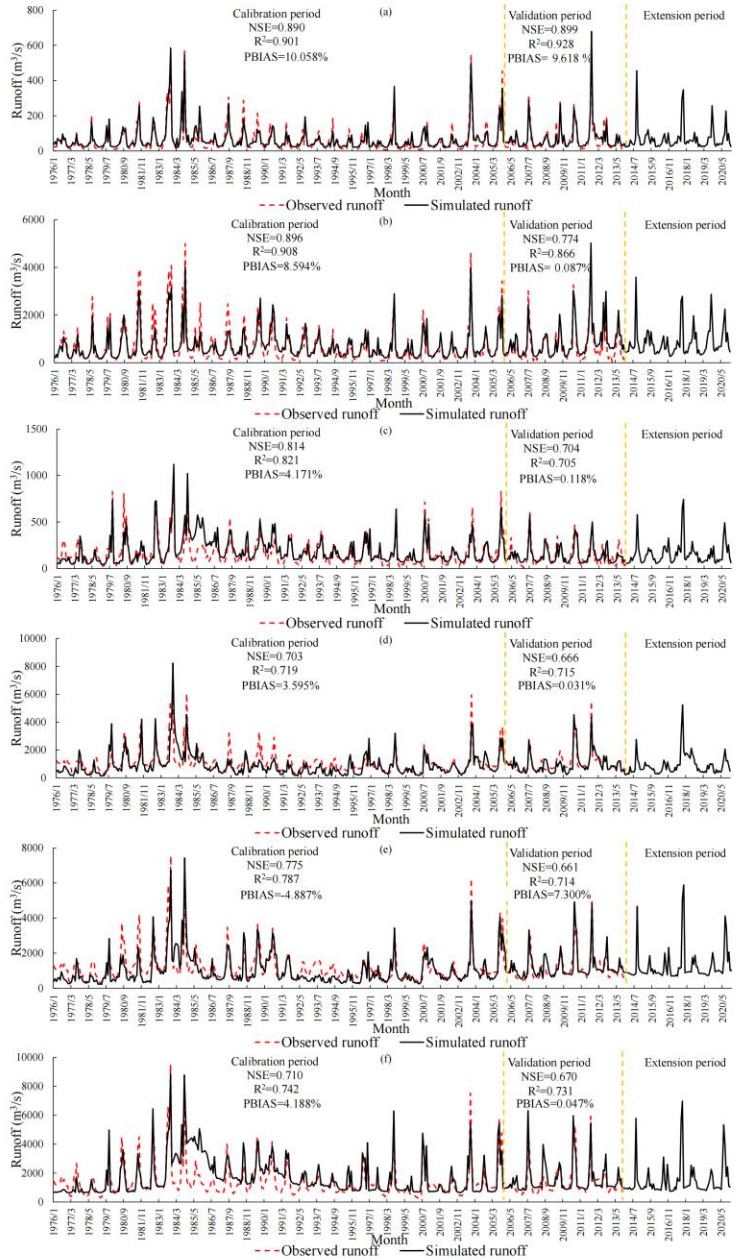

Figure 6. Calibration and validation results of simulation at hydrological stations: (a)Xiangjiangping, (b) Baihe, (c) Huanglongtan, (d) Huangjiagang, (e) Xiangyang, (f) Huangzhuang.

4.2 Multi-level ecological flows classification and calculation results

The multi-level ecological flows at HJX, AK, DJK, WFZ, and XL reservoir dam sites for each month were determined through the MTMMHC method. Their EFs are categorized into four levels: *MEF*, E_2, $OEF_{\min}$ and $OEF_{\max}$. The results at XL reservoir dam site from the MTMMHC method are presented in Table 4. Their Efs for wet, normal, and dry years show the decreasing trends, with higher values during the flood season. Its peak ecological flow occurs in August during wet years while in July during both normal and dry years. All the peak EFs for the other four sites occur between July and September. The peak EF for HJX and AK reservoir dam sites during wet, normal, and dry years occur between July and August. The peak values for DJK and WFZ are dispersed, and theyare found in September, August, and July. The EFs at the five reservoir dam sites from June to September are significantly higher than their in other months. These EFs for wet, normal, and dry years are similar to the related ecological flow quantification results in HRB (Zhang, et al., 2022; Li and Kang, 2014).

Table 4. Multi-level ecological flows resulted from MTMMHC method.

Site	Month	Hydrological years											
		Wet year				Normal year				Dry year			
		MEF (m^3/s)	E_2 (m^3/s)	OEF_{min} (m^3/s)	OEF_{max} (m^3/s)	*MEF* (m^3/s)	E_2 (m^3/s)	OEF_{min} (m^3/s)	OEF_{max} (m^3/s)	*MEF* (m^3/s)	E_2 (m^3/s)	OEF_{min} (m^3/s)	OEF_{max} (m^3/s)
XL dam site	Jan	1197	1476	1550	1668	825	849	872	910	664	666	668	670
	Feb	1265	1467	1539	1656	836	863	890	933	675	678	681	686
	Mar	1268	1486	1569	1702	842	869	896	938	685	690	696	705
	Apr	1249	1329	1426	1581	868	892	916	955	691	698	704	714
	May	1273	1675	1822	2058	861	887	912	953	705	714	723	738
	Jun	1653	1681	1877	2192	877	916	955	1017	763	786	809	846
	Jul	1818	2629	2987	3560	1288	1430	1572	1799	875	921	968	1043
	Aug	1885	2522	2849	3372	1266	1401	1537	1753	811	845	879	933
	Sep	1465	2822	3225	3869	1174	1279	1384	1553	834	879	924	997
	Oct	1368	2276	2611	3148	978	1036	1094	1186	733	752	772	802
	Nov	1315	1586	1748	2007	897	932	966	1022	691	697	704	714
	Dec	1194	1471	1549	1675	845	873	900	944	680	686	691	700

4.3 Responses of indexes in feedback loops with different clusters of IWDPs in a reservoirs group

4.3.1 Responses of indexes in feedback loops without and with IWDPs

To analyse the feedback loops of SHE nexus without (i.e., $S_{1-0-p-c}$ and $S_{1-0-4-c}$) and with IWDPs (i.e., $S_{2-3-p-c}$ and $S_{2-3-4-c}$) across the multiple temporal (i.e., monthly, seasonal and annual) and spatial (i.e., five reservoirs) scales, the differences of indexes (i.e., LRR_1, LRR_2, LRR_3 for log response ratio of the S, H, and E component) between $S_{1-0-p-c}$ and $S_{1-0-4-c}$ or between $S_{2-3-p-c}$ and $S_{2-3-4-c}$ are determined at the time scales in a reservoirs group. The results of the monthly differences are shown in Figure 7 and 8.

If there was no IWDPs and S-Priority was set, both the mean values of LRR_2 (i.e., -0.062, -0.092, -0.068, -0.094, and -0.021) and the mean values of LRR_3 (i.e., -0.270, -0.539, -0.070, -0.195, and -0.606) in five reservoirs remain below 0 as shown in Figure 7 (a). As there are a large number of negative values of LRR_2 in all reservoirs with S-Priority as shown in Figure 7 (a-1), the hydropower generation is found to be reduced in most months. However, there are still some positive values of LRR_2 in reservoirs. XL reservoir shows a higher occurrence of positive values of LRR_2 when there is abundant water such as July in 2007 and September in 2017 (i.e., 0.145 and 0.123, respectively). As shown in Figure 7 (a-2), all the five reservoirs exhibit a negative LRR_3 in all months. The value of LRR_3 for the DJK reservoir is closest to 0. The smallest mean values of LRR_3 for the XL and AK reservoirs are -0.606 and -0.539, respectively. The reduction of $EFCR_{xy}$ for DJK is smaller than those for other reservoirs due to its effective regulating. The values of $EFCR_{xy}$ for XL and AK significantly decrease due to their greater reductions of ecological flow and their higher ecological flow standards at the two reservoirs dam sites. The extreme values (e.g., lower than 90 % months values) of LRR_3 for HJX, AK, WFZ, and XL reservoirs occur in the higher water supply demand months such as June to September of each year. And Gao et al. (2023) find that the higher water supply demand, the lower ecological flow left in river. The environment conservation of downstream river systems is critically influenced by upstream water supply decisions (Gupta, 2008). There are also differences between the results of LRR_2 and LRR_3, the range of LRR_3 value is wider, while its of LRR_2 are relatively concentrated and closer to 0. Therefore, there are negative feedbacks of the S component on other two components, and these negative feedbacks of the S component on E are even more pronounced than those on H. Our findings are consistent with the results from the other SHE nexus studies (Chen et al.,2018; Khalkhali et al., 2018). It can be also found that the negative feedbacks of S on H in reservoirs are weakened or even broken, while positive feedbacks of S on H are in abundant water months.

If there was no IWDPs and H-Priority was set, the values of LRR_1 for all five reservoirs are less than zero in most months, and the mean values of LRR_3 exceed zero as shown in Figure 7 (b). The water supply for HJX, DJK, and XL is significantly decreased, with their mean values of LRR_1 are -18.345, -11.547, and -7.719, while the water supply for AK and WFZ has slight reductions (i.e., the mean values of LRR_1 are -0.162 and -0.225, respectively) as shown in Figure 7 (b-1). There are two positive values of LRR_1 for DJK reservoir occurring in January 2010 and in July 2011 (i.e., 20.324

and 0.189, respectively). In January 2010, higher water storage resulting from H-Priority increases water availability. With H-Priority, reservoirs with regulating capacity will store more water, leading to increased generation flow during dry periods (Zhang et al., 2014). While in July 2011, an increase in the discharge flow from the upstream reservoir increase the water supply. As shown in Figure 7 (b-2), the values of $EFCR_{xy}$ for HJX reservoir experiences a significant increase, with a mean value of LRR_3 of 0.922, followed by XL and AK (i.e., their mean values of LRR_3 are 0.396 and 0.143). DJK and its downstream reservoirs have negative values of LRR_3 in abundant water months because of the increased storage capacity and the reduced inflow into DJK. The water resource allocation of DJK affects the SHE system of downstream reservoirs. Wei et al. (2022) also concluded that hydropower generation is positively related to environment conservation. There are also differences between the results of LRR_1 and LRR_3, the values of LRR_3 are relatively closer to 0 than those of LRR_1. The feedbacks on S are more pronounced than on E. The extreme values of LRR_1 and LRR_3 are always found in months with small water flow in river but with high-water supply demand. Thus, H has both negative and positive feedbacks on E which is consistent with the founding by Wu et al. (2021). In abundant water months, the positive feedback can be changed into a negative one. The increased flows for hydropower generation alleviates the pressure of ecological damage in river. However, the more flows for hydropower generation from the reservoir, the less supplied amount of available water resources (Doummar et al., 2009), and leads to negative impacts on the S component.

If there was no IWDP and E-Priority was set, the mean values of LRR_1 for HJX, DJK, and XL reservoirs are -6.591, -1.740, and -5.643 as shown in Figure 7 (c-1). However, the values of LRR_1 for AK and WFZ are almost zero because their increased discharge water from upstream are prioritized to be released for hydropower generation, and no excess is for water supply. Thus, the prioritizing E has less impact on S for reservoirs due to the main function of hydropower generation. DJK and XL exhibit some positive values of LRR_1 because the increased inflows from upstream. Therefore, the increased inflow to upstream reservoirs alleviates the negative feedbacks of E on S in downstream reservoirs. As shown in Figure 7 (c-2), the mean values of LRR_2 for HJX, AK, DJK, and WFZ reservoirs are 0.127, 0.045, 0.022, and 0.037. While XL has a negative mean value of LRR_2 at -0.058, it experiences more decreases in hydropower generation primarily due to its smaller installed capacity (Zhang, 2008). Negative values of LRR_2 can be found in abundant water months. The ranges of LRR_1 and LRR_2 are also different. The former one is wide while the other one is narrow and their values are closer to zero. Therefore, the feedbacks of the E component on S are stronger than those on H. According to the values of LRR_n, Negative feedbacks of the E component on S for reservoirs has been found in the scenario that main function is water supply while no significant effect on reservoirs has been found in the scenario that main function is hydropower generation. There are both negative and positive feedbacks of the E component on H while the negative feedbacks are grown in abundant water months.

The differences between the $S_{2\text{-}3\text{-}p\text{-}c}$ and $S_{2\text{-}3\text{-}4\text{-}c}$ scenarios were determined to analyse the feedback loops with IWDPs as shown in Figure 8 (a), (b), and (c). It can be found that the positive or negative signs of the LRR_n values with IWDPs are consistent with those without IWDPs. If there are IWDPs and S-Priority was set, the mean value of LRR_3 for XL shows an increase while all the values of LRR_2 and LRR_3 for other four reservoirs are lower than those without IWDPs as shown in Figure 8 (a) and Figure 7 (a). The mean values of LRR_2 with IWDPs for the five reservoirs are -0.130, -0.114, -0.165, -0.209, and -0.066, and the mean values of LRR_3 are -0.908, -0.753, -1.253, -1.125, and -0.285. And DJK reservoir get more extreme values due to the impacts of IWDPs. The values of LRR_2 with IWDPs are lower than -0.450 (i.e., the minimum value of LRR_2 without IWDPs) in 6 % of the months while the values of LRR_3 are lower than -1.404 (i.e., the minimum value of LRR_3 without IWDPs) in 8 % of the months. It is evident that IWDPs strengthens the negative feedbacks of the S component on the other two components in HJX, AK, DJK and WFZ, while IWDPs weaken negative feedbacks of S on E for XL. As shown in Figure 8 (b-1), If there were IWDPs and H-Priority was set, the mean values of LRR_1 for HJX, AK, and XL reservoirs significantly decrease to -18.777, -0.783, and -12.242, but the mean value of LRR_1 for DJK reservoir are increased by 3.491 due to IWDPs. The operation of the Han-to-Wei Water Diversion Project, the Middle Route of the South-to-North Water Diversion Project, and the Northern Hubei Water Resources Allocation

Project in DJK and upstream reservoirs have reduced the regional water supply (Hong et al., 2016), the differences of water supply between the $S_{2\text{-}3\text{-}2\text{-}c}$ and $S_{2\text{-}3\text{-}4\text{-}c}$ scenarios remain negligible despite further reductions in water supply with H-Priority. As shown in Figure 8 (b-2), The values of LRR_3 for HJX, AK, DJK, and WFZ increase further than them in Figure 7 (b-2) without IWDPs, indicating the positive feedbacks of the H component on E get strengthen with the impacts of IWDPs. The values of LRR_3 for XL decrease slightly due to the positive feedbacks of the H component on E and the IWDPs impacts. As shown in Figure 8 (c-1), If there were IWDPs and E-Priority was set, the mean values of LRR_1 for HJX and XL decrease by 5.107 and 2.766, respectively. And the mean values of LRR_1 for AK and WFZ remain at almost zero, while the mean value of LRR_1 for DJK increases by 0.259 with IWDPs compared to without IWDPs. As shown in Figure 8 (c-2), the mean values of LRR_2 for five reservoirs increase by 0.176, 0.036, 0.031, 0.021 and 0.008 with IWDPs compared to without IWDPs. The positive feedbacks of E component on H are strengthened, while the negative feedbacks are weakened.

Therefore, negative feedbacks can be found between S and H, and between S and E while positive feedbacks can be found between H and E in a reservoirs group without IWDPs. These negative and positive feedbacks in our study have also been found in other studies on the SHE nexus (Doummar et al., 2009; Wu et al., 2022). As our proposed framework is valid, the results also reinforce the robustness of the identified feedbacks in different contexts. It has been found that there are a few positive feedbacks between S and H in abundant water months even the spilled water leads to a reduction in hydropower generation (Jiang et al., 2018). Thus, the increasing water storage or increasing water supply still can ensure hydropower generation. However, the positive feedbacks between H and E are weakened or even turn to be negative in the small installed hydropower generation capacity reservoirs (e.g., the XL reservoir) even in abundant water months, particularly. The negative feedbacks between S and H, and between S and E are strong in low flow months due to the high-water supply demand. More competitions for water can be found among S, H and E in low flow months, and their negative feedbacks of the SHE nexus have found to be strengthened. Feedback loops of SHE nexus in reservoirs with regulation function (e.g., AK and DJK) remain stable under the varying inflow conditions. These reservoirs reasonably allocate water among S, H and E components to prevent strengthening of negative feedbacks in low flow months. Furthermore, increasing hydropower generation flow might have impacts on downstream water quality and biodiversity (Botelho et al., 2017; Martinez et al., 2019), the feedbacks of H on E are enhanced. If there were IWDPs, it is evident that feedback loops of SHE nexus across different spatial scales exhibit strong responses. As IWDPs export or import water to or from an area, the amount of available water has to be altered. It can prompt a redistribution and re-planning of the available water (Li, et al., 2014). And the redistribution and re-planning can significantly impact on feedback loops of SHE nexus. Although strong responses occur in feedback loops of SHE nexus, its positive or negative nature of feedback among these components remains stable with impacts of IWDPs. Thus, the redistribution and re-planning of available water can not alter their competitions and collaborations among the components of the SHE nexus.

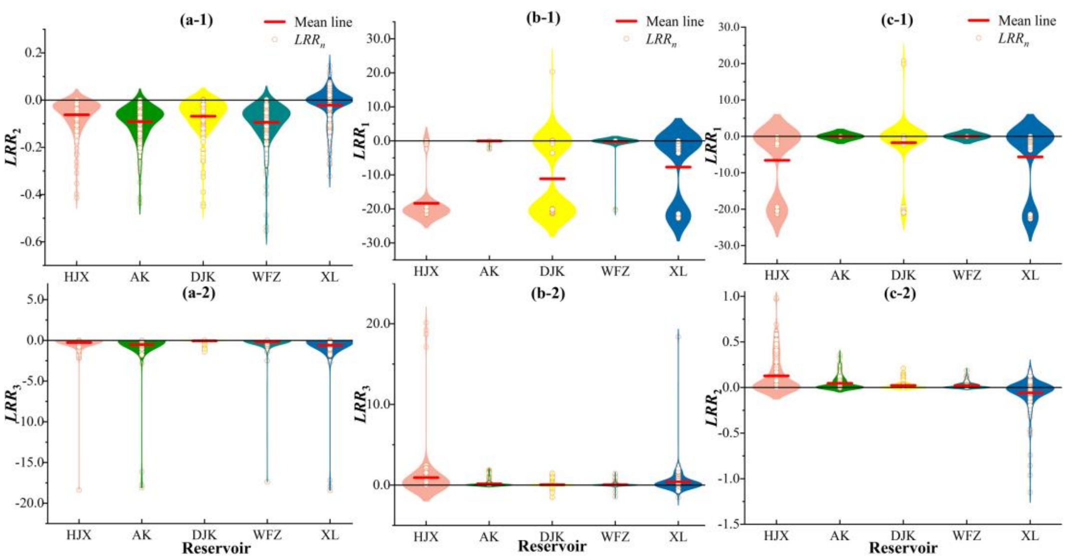

Figure 7. the differences of indexes (i.e., LRR_1, LRR_2, LRR_3 for log response ratio of the S, H, and E component) without IWDPs (i.e., between $S_{1\text{-}0\text{-}p\text{-}c}$ and $S_{1\text{-}0\text{-}4\text{-}c}$) at the monthly scale: (a-1) are LRR_2 with the highest priority in S (i.e., between $S_{1\text{-}0\text{-}1\text{-}1}$ and $S_{1\text{-}0\text{-}4\text{-}2}$), (a-2) are LRR_3 with the highest priority in S (i.e., between $S_{1\text{-}0\text{-}1\text{-}2}$ and $S_{1\text{-}0\text{-}4\text{-}3}$), (b-1) are LRR_1 with the highest priority in H (i.e., between $S_{1\text{-}0\text{-}2\text{-}1}$ and $S_{1\text{-}0\text{-}4\text{-}1}$), (b-2) are LRR_3 with the highest priority in H (i.e., between $S_{1\text{-}0\text{-}2\text{-}2}$ and $S_{1\text{-}0\text{-}4\text{-}3}$), (c-1) are LRR_1 with the highest priority in E (i.e., between $S_{1\text{-}0\text{-}3\text{-}1}$ and $S_{1\text{-}0\text{-}4\text{-}1}$), (c-2) are LRR_2 with the highest priority in E (i.e., between $S_{1\text{-}0\text{-}3\text{-}2}$ and $S_{1\text{-}0\text{-}4\text{-}2}$).

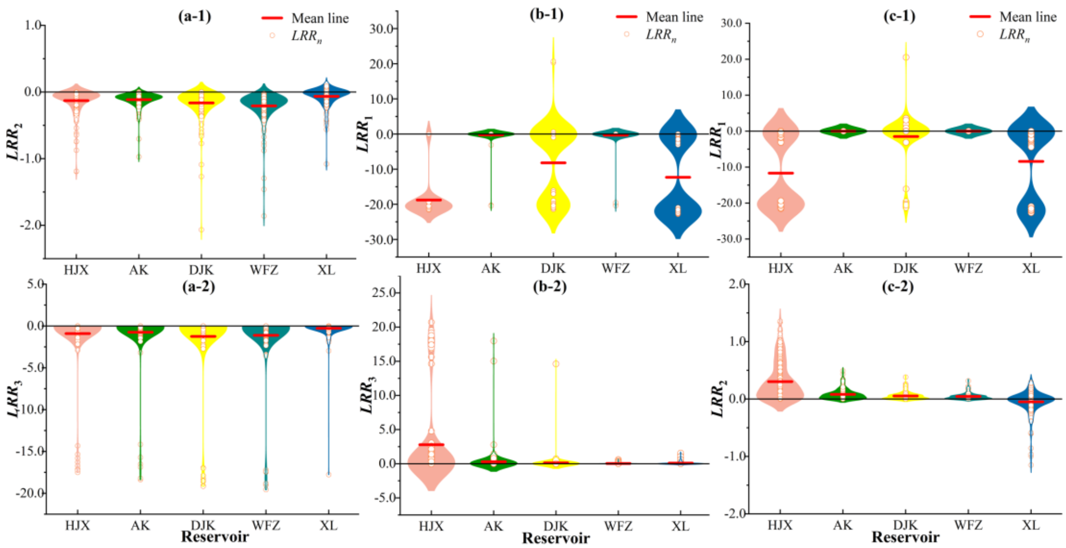

Figure 8. the differences of indexes (i.e., LRR_1, LRR_2, LRR_3 for log response ratio of the S, H, and E component) with IWDPs (i.e., between $S_{2\text{-}3\text{-}p\text{-}c}$ and $S_{2\text{-}3\text{-}4\text{-}c}$) at the monthly scale: (a-1) are LRR_2 with the highest priority in S (i.e., between $S_{2\text{-}3\text{-}1\text{-}1}$ and $S_{2\text{-}3\text{-}4\text{-}2}$), (a-2) are LRR_3 with the highest priority in S (i.e., between $S_{2\text{-}3\text{-}1\text{-}2}$ and $S_{2\text{-}3\text{-}4\text{-}3}$), (b-1) are LRR_1 with the highest priority in H (i.e., between $S_{2\text{-}3\text{-}2\text{-}1}$ and $S_{2\text{-}3\text{-}4\text{-}1}$), (b-2) are LRR_3 with the highest priority in H (i.e., between $S_{2\text{-}3\text{-}2\text{-}2}$ and $S_{2\text{-}3\text{-}4\text{-}3}$), (c-1) are LRR_1 with the highest priority in E (i.e., between $S_{2\text{-}3\text{-}3\text{-}1}$ and $S_{2\text{-}3\text{-}4\text{-}1}$), (c-2) are LRR_2 with the highest priority in E (i.e., between $S_{2\text{-}3\text{-}3\text{-}2}$ and $S_{2\text{-}3\text{-}4\text{-}2}$).

In this study, March, April, May are taken as spring, June, July and August are taken as summer, September, October and November are taken as autumn, and December, January and February of the following year are taken as winter. The values of LRR_n for five reservoirs at seasonal scale are shown in Figure 9. If there was no IWDP but S-Priority was still set, positive values of LRR_2 for HJX and XL are found in summer, while all negative values of LRR_2 for other three reservoirs are found in all seasons as shown in Figure 9 (a). The mean values of LRR_3 for the five reservoirs are -0.119, -0.106, -0.022, -0.020, and -0.669, and all values of LRR_3 are negative in all seasons. If there were IWDPs and S-Priority was set, the mean value of LRR_3 for XL increases while the values of LRR_2 and LRR_3 for other four reservoirs are less than those without IWDPs as shown in Figure 9 (b). These negative values indicate that IWDPs significantly strengthen the negative feedbacks of the S component on H and E in reservoirs and weaken negative feedback of S on E in XL. If there was no IWDPs but H-Priority was set, negative values of LRR_1 and positive values of LRR_3 are found for the five reservoirs as shown in Figure 9 (c). For HJX, DJK and XL reservoirs, the negative values of LRR_1 are found in winter while zero values of LRR_1 are found in summer. The mean values of LRR_1 are close to zero in AK and WFZ reservoirs in all seasons. Positive values of LRR_3 are smaller in HJX, AK, DJK and WFZ reservoirs, while those in XL are greater in winter with a low flow. If there were IWDPs and H-Priority was set, the values of LRR_1 for all reservoirs are lower than those without IWDPs as shown in Figure 9 (d). Values of LRR_3 for HJX, AK, DJK and WFZ reservoirs are greater than those without IWDPs, while those for XL are close to zero. If there was no IWDPs and E-Priority was set, negative values of LRR_1 for HJX, DJK, WFZ and XL reservoirs can be found in almost every season, while zero values of LRR_1 for AK reservoir can be found in all seasons. As shown in Figure 9 (e), two positive values of LRR_1 for DJK are found in spring and in winter of 2007 due to the increased discharge water from AK reservoir. The positive values of LRR_2 for the five reservoirs are found in most seasons, but few negative values are found in summer. If there were IWDPs and E-Priority was set, more positive values of LRR_2 for five reservoirs and less negative values of LRR_1 are found in HJX, DJK, WFZ and XL reservoirs. Therefore, negative feedbacks can be found between S and H, and between S and E while positive feedbacks can be found between H and E in most seasons in a reservoirs group. These feedbacks are strengthened in winter, while positive feedbacks between S and H and negative feedbacks between H and E are found in summer. IWDPs strongly impact these feedback loops, but the positive or negative nature of feedbacks among SHE remains stable at seasonal scale.

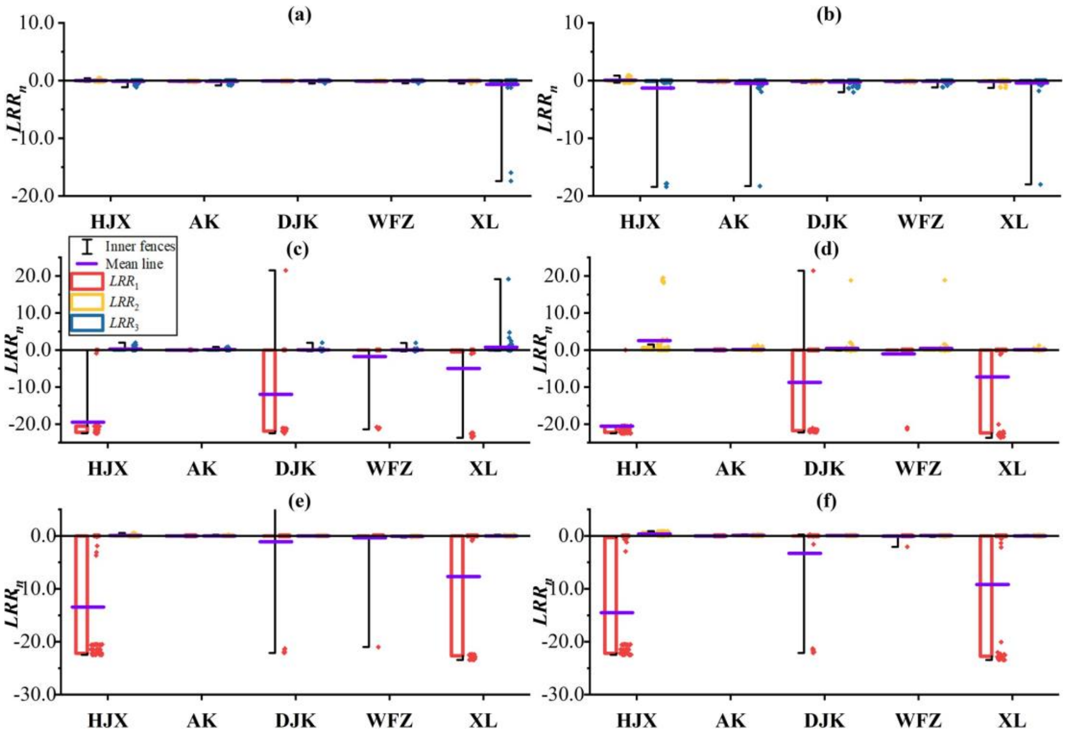

Figure 9. ***LRR**$_n$* **with different highest priorities (i.e., between** $S_{w\text{-}m\text{-}1\text{-}c}$ **and** $S_{w\text{-}m\text{-}4\text{-}c}$**) at the seasonal scale: (a) and (b) are** ***LRR**$_n$* **with the highest priority in S without IWDPs (i.e., between** $S_{1\text{-}0\text{-}1\text{-}c}$ **and** $S_{1\text{-}0\text{-}4\text{-}c}$**) and with IWDPs (i.e., between** $S_{2\text{-}3\text{-}1\text{-}c}$ **and** $S_{2\text{-}3\text{-}4\text{-}c}$**), (c) and (d) are** ***LRR**$_n$* **with the highest priority in H without IWDPs (i.e., between** $S_{1\text{-}0\text{-}2\text{-}c}$ **and** $S_{1\text{-}0\text{-}4\text{-}c}$**) and with IWDPs (i.e., between** $S_{2\text{-}3\text{-}2\text{-}c}$ **and** $S_{2\text{-}3\text{-}4\text{-}c}$**). (e) and (f) are** ***LRR**$_n$* **with the highest priority in E without IWDPs (i.e., between** $S_{1\text{-}0\text{-}3\text{-}c}$ **and** $S_{1\text{-}0\text{-}4\text{-}c}$**) and with IWDPs (i.e., between** $S_{2\text{-}3\text{-}3\text{-}c}$ **and** $S_{2\text{-}3\text{-}4\text{-}c}$**).**

The values of LRR_n for five reservoirs at annual scale are shown in Figure 10. If there was no IWDPs and S-Priority was set, values of LRR_2 for HJX, AK, WFZ reservoirs are negative during 2006-2020 as shown in Figure 10 (a-1). There are two positive values of LRR_2 for DJK in 2010, 2018, and one positive values for XL in 2020. And there is abundant water in all these three years. The minimum values of LRR_2 for five reservoirs are both found in the driest year. And there are more small values in AK and WFZ. The mean values of LRR_3 for five reservoirs are -0.020, -0.026, -0.034, -0.058, and -0.062 as shown in Figure 10 (a-2). The small values of LRR_3 for five reservoirs are found in dry years or high ecological flow requirement years such as 2010, 2011 and 2017. Downstream reservoirs can bring stronger negative feedbacks of S on E, so WFZ and XL have more small values of LRR_3. If there was no IWDPs but H-Priority was still set, the zero values of LRR_1 for AK and WFZ are found in all years, and WFZ gets more negative values of LRR_1. The positive values of LRR_3 for five reservoirs are found in abundant water years as shown in Figure 10(b-2), while negative values of LRR_2 for DJK and its upstream reservoirs are found because of the increased water storage from DJK in these years. If there was no IWDPs but E-Priority was still set, negative values of LRR_1 for HJX, DJK and XL and the positive values of LRR_2 can be found in dry years and high ecological flow requirement years as shown in Figure 10 (c-1). The negative values of LRR_2 are mainly found in abundant water years as shown in Figure 10 (c-2). As shown in Figure 10 (d), (e), (f), negative and positive values of LRR_n for HJX, AK, DJK, WFZ, and values of LRR_1, LRR_2 for XL turn to be more extreme than those without IWDPs. The values of LRR_3 for XL are closer to zero if there were IWDPs.

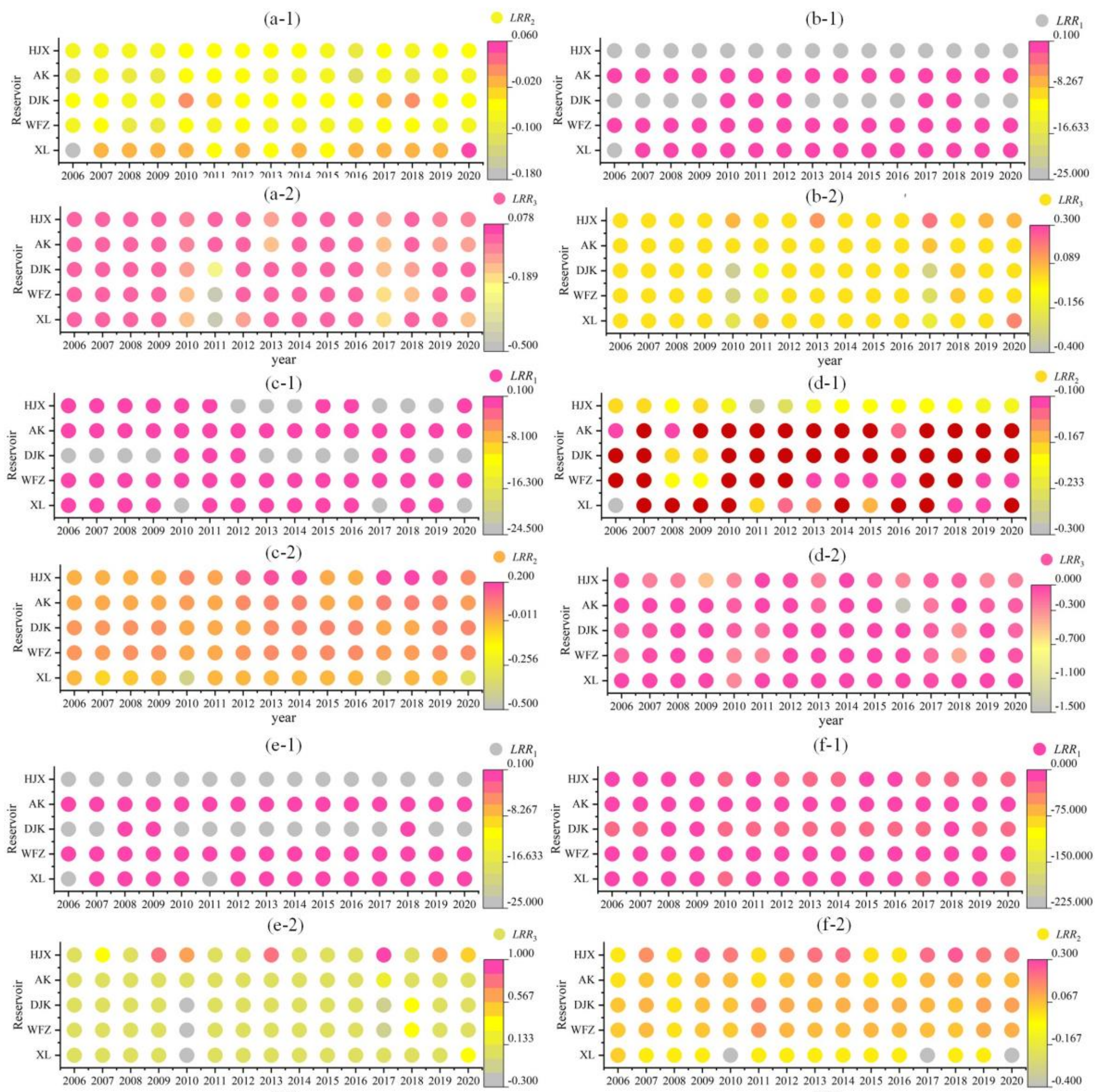

Figure 10. LRR_n without and with IWDPs at annual scale: (a-1) and (a-2) are LRR_2 and LRR_3 with the highest priority in S without IWDPs (i.e., between $S_{1\text{-}0\text{-}1\text{-}c}$ and $S_{1\text{-}0\text{-}4\text{-}c}$), (b-1) and (b-2) LRR_1 and LRR_3 with

the highest priority in H without IWDPs (i.e., between $S_{1\text{-}0\text{-}2\text{-}c}$ and $S_{1\text{-}0\text{-}4\text{-}c}$), (c-1) and (c-2) are LRR_1 and LRR_2 with the highest priority in E without IWDPs (i.e., between $S_{1\text{-}0\text{-}3\text{-}c}$ and $S_{1\text{-}0\text{-}4\text{-}c}$), (d-1) and (d-2) LRR_2 and LRR_3 with the highest priority in S with IWDPs (i.e., between $S_{2\text{-}3\text{-}1\text{-}c}$ and $S_{2\text{-}3\text{-}4\text{-}c}$), (e-1) and (e-2) are LRR_1 and LRR_3 with the highest priority in H with IWDPs(i.e., between $S_{2\text{-}3\text{-}2\text{-}c}$ and $S_{2\text{-}3\text{-}4\text{-}c}$), (f-1) and (f-2) LRR_1 and LRR_2 with the highest priority in E with IWDPs(i.e., between $S_{2\text{-}3\text{-}3\text{-}c}$ and $S_{2\text{-}3\text{-}4\text{-}c}$).

Therefore, signs of mean values of LRR_n at seasonal and annual scales are consistent with those at monthly scale, so the feedback loops of SHE nexus exhibit intrinsic similarity and stability across different time scales. Compared with the values of LRR_n at monthly scale, the values at the seasonal scale show its stronger periodic variations. Based on the variations in LRR_n and the mathematical implications of LRR_1, LRR_2, and LRR_3, this study found that these periodic variations align closely with the runoff variations, and the temporal and spatial variations in feedback loops are primarily attributed to variations in runoff. The wavelet transform analysis has also been applied in the runoffs for HJX, AK, DJK, WFZ, and XL dam sites. And the results are in consisted with that in Hutuo River Basin (Xu et al., 2018), the periodic variations have been found at the seasonal scale. The LRR_n values at the seasonal scale can help analyze the variations in periodic feedback loops. Different from the monthly or seasonal scales, results at the annual scale reveal the long-term trends and periodic variations in the inter-annual and spatial trends of the SHE nexus from a macro perspective. The impacts of reservoir operation and the regulation on SHE nexus can be clearly simulated and observed at the monthly scale, so the immediate changes in the nexus at monthly scale can provide information for short-term decision-making in reservoirs.

4.3.2 Responses of indexes in feedback loops with only water donation, water receiving, and both donation and receiving

To analyse the impacts of only water donation (i.e., $S_{2\text{-}1\text{-}p\text{-}c}$ and $S_{1\text{-}0\text{-}4\text{-}c}$), only water receiving (i.e., $S_{2\text{-}2\text{-}p\text{-}c}$ and $S_{1\text{-}0\text{-}4\text{-}c}$), and both donation and receiving (i.e., $S_{2\text{-}3\text{-}p\text{-}c}$ and $S_{1\text{-}0\text{-}4\text{-}c}$) on feedback loops of SHE nexus across the multiple temporal and spatial scales, the differences of indexes between $S_{2\text{-}m\text{-}p\text{-}c}$ and $S_{1\text{-}0\text{-}4\text{-}c}$ are determined in a reservoirs group. The results of the monthly differences are shown in Figure 11-13.

If there was only water donation and S-Priority was set, values of LRR_2 and LRR_3 for five reservoirs are negative and lower than those without IWDPs as shown in Figure 11 (a-1) and (a-2). More small negative values are found in DJK, water donation has negative impacts on the negative feedback of S on H and E for five reservoirs. Wei et al. (2022) demonstrate water diversion is negatively related to the hydropower generation and the environment conservation. If there was only water receiving and S-Priority was set, values of LRR_2 and LRR_3 for HJX and AK are the same as those without IWDPs. Meanwhile, for DJK, WFZ, and XL, the values are close to zero. XL exhibits a lot of positive values of LRR_3 as shown in Figure 11 (b-1) and (b-2). If there were both water donation and receiving, the mean values of LRR_2 for five reservoirs are -0.594, -0.263, -0.484, -0.468 and -0.091, and mean values of LRR_3 for five reservoirs are -6.117, -1.500, -2.011, -1.598 and 0.143 as shown in Figure 11 (c-1) and (c-2). There are negative impacts on negative feedbacks of S on H and E for HJX, AK, DJK and WFZ and positive impacts of the negative feedbacks of S on E for XL.

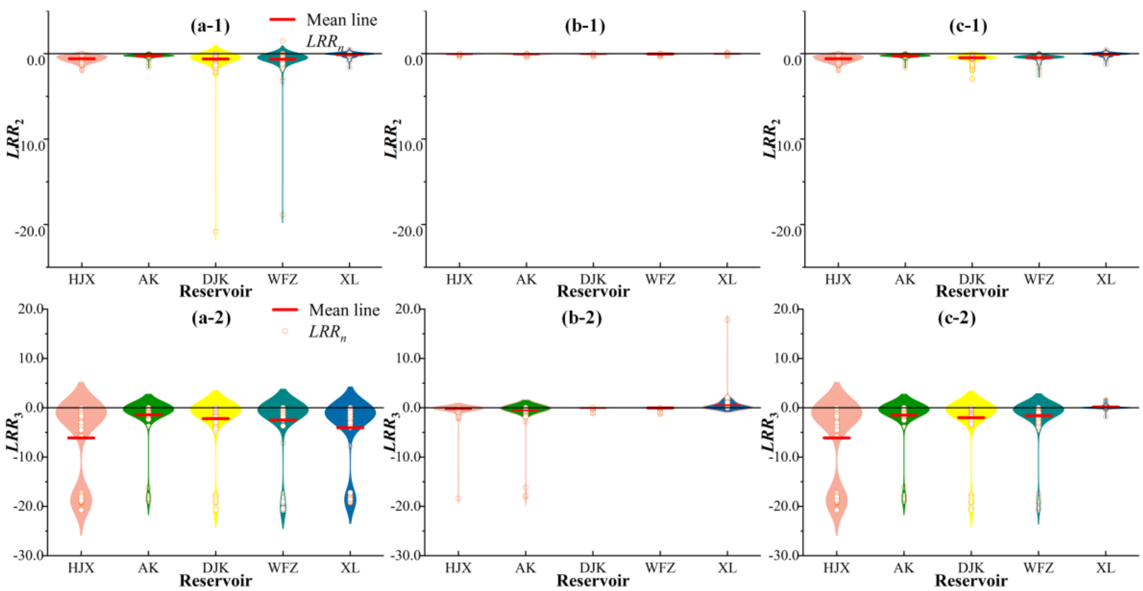

Figure 11. LRR_n values when there are different clusters of IWDPs and S-Priority was set at the monthly scale: (a-1) and (a-2) are LRR_2 and LRR_3 when there is only water donation (i.e., between $S_{2\text{-}1\text{-}1\text{-}c}$ and $S_{1\text{-}0\text{-}4\text{-}c}$), (b-1) and (b-2) are LRR_2 and LRR_3 when there is only water receiving (i.e., between $S_{2\text{-}2\text{-}1\text{-}c}$ and $S_{1\text{-}0\text{-}4\text{-}c}$), (c-1) and (c-2) are LRR_2 and LRR_3 when there are both donation and receiving (i.e., between $S_{2\text{-}3\text{-}1\text{-}c}$ and $S_{1\text{-}0\text{-}4\text{-}c}$).

If there was only water donation and H-Priority was set, values of LRR_1 and LRR_3 for five reservoirs are lower than those without IWDPs as shown in Figure 12 (a-1) and (a-2). Negative values of LRR_3 for five reservoirs are found in low flow months such as November, December and January. Thus, water donation is found to have negative impacts on feedbacks of H on S and E, especially in low flow months. If there was only water receiving and H-Priority was set, values of

LRR_1 and LRR_3 for DJK, WFZ and XL are greater than those without IWDPs as shown in Figure 12 (b-1) and (b-2). Water receiving has positive impacts on feedbacks of H on S and E. If there were both water donation and receiving and H-Priority was set, the mean values of LRR_1 and LRR_3 for DJK, WFZ and XL are still lower than those without IWDPs. And the mean value of LRR_3 for XL is greater than those without IWDPs as shown in Figure 12 (c-1) and (c-2).

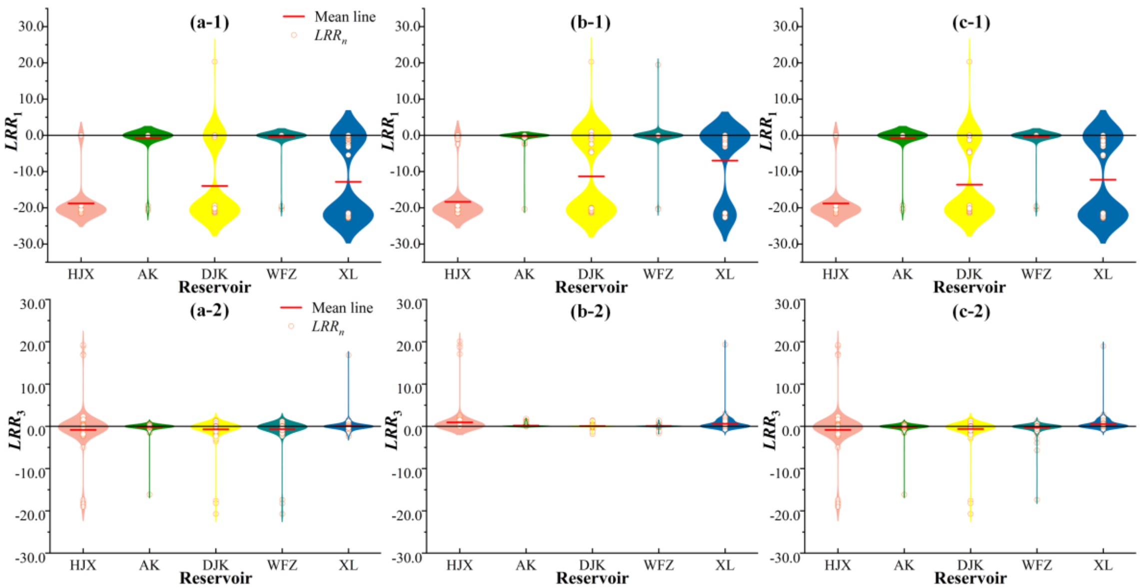

Figure 12. *LRR_n* values when there are different clusters of IWDPs and H-Priority was set at the monthly scale: (a-1) and (a-2) are *LRR_2* and *LRR_3* when there is only water donation (i.e., between $S_{2-1-2-c}$ and $S_{1-0-4-c}$), (b-1) and (b-2) are *LRR_2* and *LRR_3* when there is only water receiving (i.e., between $S_{2-2-2-c}$ and $S_{1-0-4-c}$), (c-1) and (c-2) are *LRR_2* and *LRR_3* when there are both donation and receiving(i.e., between $S_{2-3-2-c}$ and $S_{1-0-4-c}$).

If there was only water donation and E-Priority was set, then values of LRR_1 and LRR_2 for five reservoirs are shown in Figure 13 (a-1) and (a-2). The mean values of LRR_1 for these five reservoirs are -11.699, -0.002, -7.228, -0.218, and -9.139, respectively. And the mean values of LRR_2 are -0.161, -0.067, -0.287, -0.296, and -0.083. All these values are lower than the those without IWDPs. Different from the values of LRR_n without IWDPs, there are no positive values of LRR_1 for DJK and few positive values of LRR_2 for five reservoirs due to the decreased inflows from upstream with water donation. If there was only water receiving and E-Priority was set, values of LRR_1 and LRR_2 for DJK, WFZ and XL are greater than those without IWDPs. If there were both water donation and receiving and E-Priority was set, the mean values of LRR_1 and LRR_2 for DJK, WFZ and XL are still lower than those without IWDPs as shown in Figure 13 (c-1) and (c-2).

Therefore, it is evident that water donation has negative impacts on the negative feedbacks between S and H, on the negative feedbacks between S and E, and on the positive feedbacks between H and E while receiving water has positive impacts on all these feedbacks. Water donation results in a reduction of available water (Mok et al., 2015; Wu et al., 2022) and leads to lower flow. More competition for water can be found among S, H and E, and negatively impacts on the feedbacks. Less competition is found among S, H and E in water receiving areas, and it has positive impacts on their feedbacks.

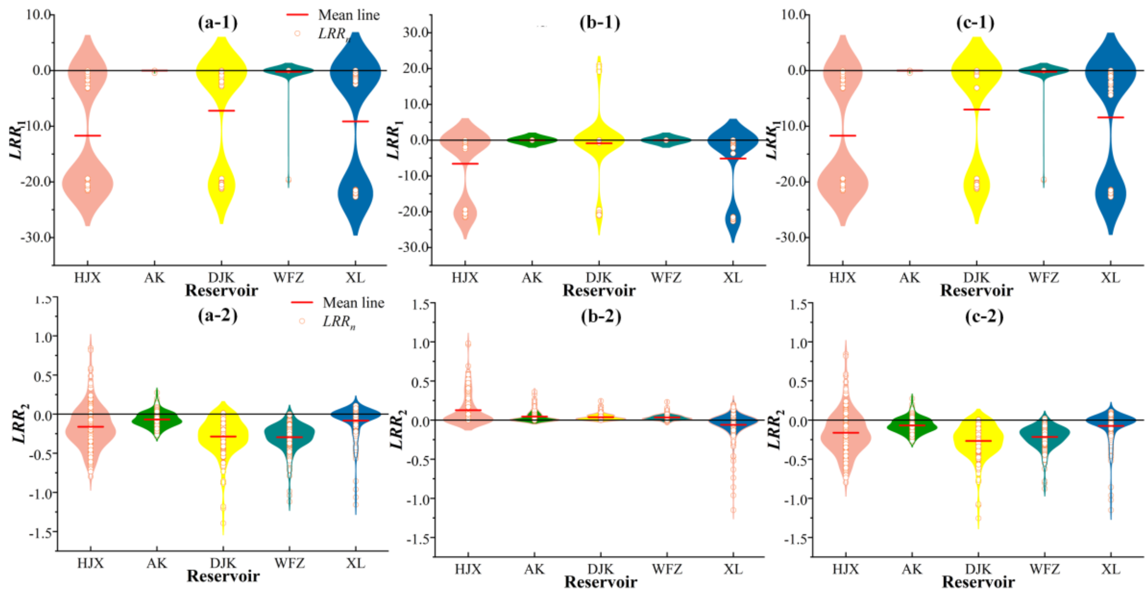

Figure 13. LRR_n values when there are different clusters of IWDPs and E-Priority was set at the monthly scale: (a-1) and (a-2) are LRR_1 and LRR_2 when there is only water donation (i.e., between $S_{2\text{-}1\text{-}3\text{-}c}$ and $S_{1\text{-}0\text{-}4\text{-}c}$), (b-1) and (b-2) are LRR_1 and LRR_2 when there is only water receiving (i.e., between $S_{2\text{-}2\text{-}3\text{-}c}$ and $S_{1\text{-}0\text{-}4\text{-}c}$), (c-1) and (c-2) are LRR_1 and LRR_2 when there are both donation and receiving (i.e., between $S_{2\text{-}3\text{-}3\text{-}c}$ and $S_{1\text{-}0\text{-}4\text{-}c}$).

If there was only water donation and S-Priority was set, values of LRR_2 and LRR_3 as shown in Figure 14(a-1) are lower than those without IWDPs in all seasons as shown in Figure 9 (a). If there was only water receiving and S-Priority was set, mean values of LRR_2 and LRR_3 for DJK, WFZ and XL (i.e., -0.040, -0.045, -0.026 and -0.012, -0.002, 0.703) as shown in Figure 14 (a-2) are all greater than those without IWDPs. If there were both water donation and receiving and S-Priority was set, mean values of LRR_2 for five reservoirs decrease by 0.334, 0.118, 0.336, 0.362 and 0.074 compared to those without IWDPs. Mean values of LRR_3 for HJX, AK, DJK and WFZ decrease by 3.692, 0.520, 0.724, 0.550, and its for XL increases by 0.894 compared to those without IWDPs as shown in Figure 14 (a-3). If there was only water donation and H-Priority was set, values of LRR_1 and LRR_3 as shown in Figure 14(b-1) are lower than those without IWDPs. Water donation has negative impacts on feedbacks of H on S for HJX, DJK and XL. If there was only water receiving and H-Priority was set, mean values of LRR_2 for DJK, WFZ and XL increase by 0.730, 0.318 and 0.729, and mean values of LRR_3 for DJK, WFZ and XL increase by 0, 0.009 and 0.006 compared to those without IWDPs. If there were both water donation and receiving and H-Priority was set, mean values of LRR_2 for five reservoirs are -20.579, 0, -14.490, -1.752, -8.068, and mean values of LRR_3 for five reservoirs are 0.008, 0.010, -0.050, -0.022 and 0.680 as shown in Figure 14 (b-3). If there was only water donation and E-Priority was set, it can be found that values of LRR_1 and LRR_2 in all seasons are lower than those without IWDPs as shown in Figure 14(c-1). Mean values of LRR_1 for five reservoirs decrease by 14.581, 0.010, 9.392, 1.043 and 10.376, and mean values of LRR_2 for five reservoirs decrease by 0.054, 0.043, 0.277, 0.331 and 0.221. Water donation has negative impacts on the feedbacks of E on S and H. If there was only water receiving and E-Priority was set, mean values of LRR_1 and LRR_2 for DJK, WFZ and mean values of LRR_1 for XL are greater than those without IWDPs, while mean values of LRR_2 for XL get an increase as shown in Figure 14 (c-2). If there were both water donation and receiving and E-Priority was set, Values of LRR_1 and LRR_2 for DJK and WFZ and values of LRR_1 for XL as shown in Figure 14 (c-3) are greater than those with only water donation, while lower than those without IWDPs. While values of LRR_2 for XL are greater than those without IWDPs because of the reduced spilled water. Therefore, values of LRR_n at seasonal scale demonstrate a consistent conclusion with those at the monthly scale. Moreover, the values of LRR_n are relatively stable in summer, while they change greatly in winter at seasonal scale. The impacts of IWDPs on SHE nexus are more significant in low flow seasons.

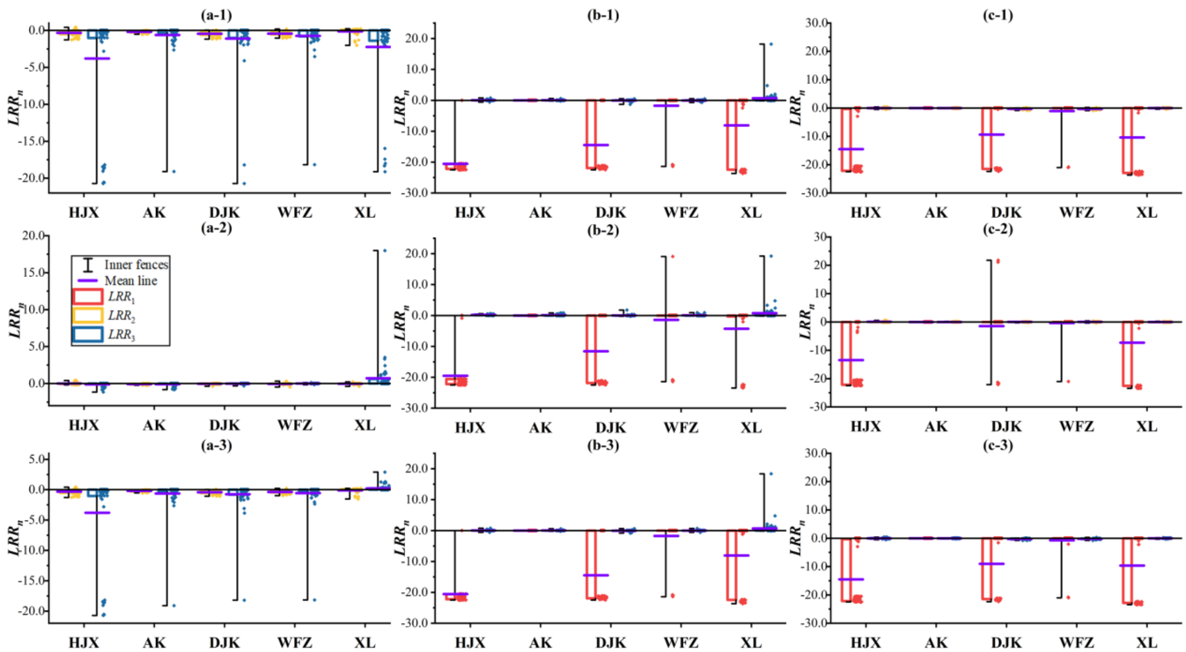

Figure 14. LRR_n values when there are different clusters of IWDPs at the seasonal scale: (a-1), (a-2) and (a-3) are LRR_n when there was only water donation, when there was only water receiving, when there were both donation and receiving and S-Priority was set (i.e., between $S_{2\text{-}m\text{-}1\text{-}c}$ and $S_{1\text{-}0\text{-}4\text{-}c}$); (b-1), (b-2) and (b-3) are those when H-Priority was set (i.e., between $S_{2\text{-}m\text{-}2\text{-}c}$ and $S_{1\text{-}0\text{-}4\text{-}c}$); (c-1), (c-2) and (c-3) are those when E-Priority was set (i.e., between $S_{2\text{-}m\text{-}3\text{-}c}$ and $S_{1\text{-}0\text{-}4\text{-}c}$).

The results of the annual differences are shown in Figure 15-17. If there was only water donation and S-Priority was set, values of LRR_2 and LRR_3 are lower than those without IWDPs as shown in Figure 10 (a-1) and (a-2). The values of LRR_2 and LRR_3 for HJX, DJK and XL decrease significantly, and these three reservoirs are severely impacted by water donation. If there was only water receiving and S-Priority was set, values of LRR_2 and LRR_3 for DJK, WFZ and XL show a slight increase. If there were both water donation and receiving and S-Priority was set, only XL has greater values of LRR_2 and LRR_3 than those without IWDPs.

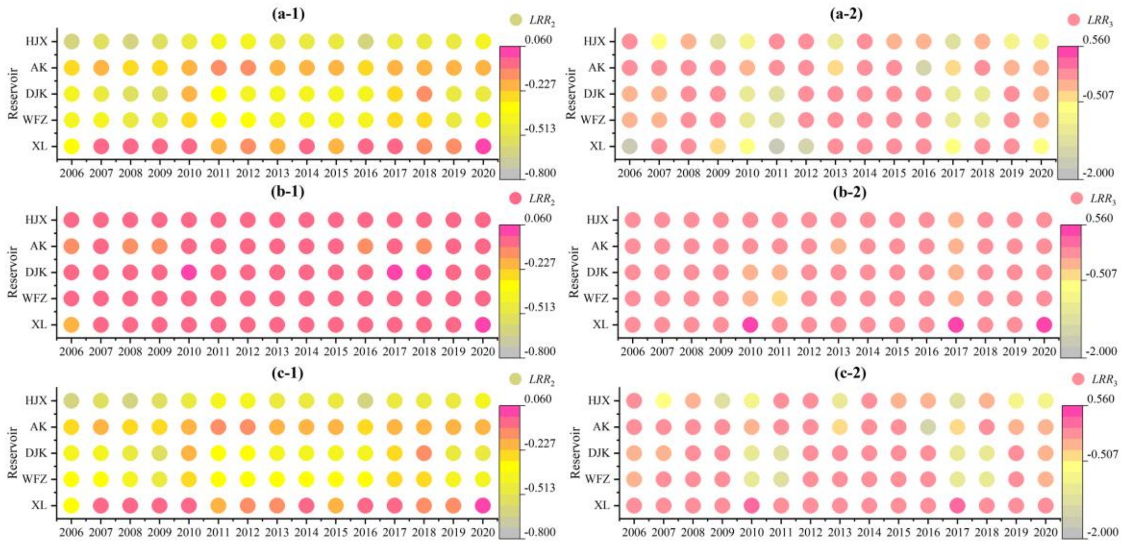

Figure 15. LRR_n values when there are different clusters of IWDPs and S-Priority was set at the annual scale: (a-1) and (a-2) are LRR_2 and LRR_3 when there was only water donation (i.e., between $S_{2\text{-}1\text{-}1\text{-}c}$ and $S_{1\text{-}0\text{-}4\text{-}c}$), (b-1) and (b-2) are those when there was only water receiving (i.e., between $S_{2\text{-}2\text{-}1\text{-}c}$ and $S_{1\text{-}0\text{-}4\text{-}c}$), (c-1) and (c-2) are those when there were both donation and receiving (i.e., between $S_{2\text{-}3\text{-}1\text{-}c}$ and $S_{1\text{-}0\text{-}4\text{-}c}$).

If there was only water donation and H-Priority was set, HJX, DJK and XL have more negative values of LRR_1 as shown in Figure 16 (a-1), and all of these values are lower than those without IWDPs. DJK, WFZ and XL has more smaller values of LRR_3 as shown in Figure 16(a-2) than those without IWDPs. Smaller values of LRR_1 and LRR_3 for reservoirs are found in low flow years. If there was only water receiving and H-Priority was set, values of LRR_1 and LRR_3 for DJK, WFZ and XL increase only in low flow years as shown in Figure 16 (b-1) and (b-2). If there were both water donation and receiving and H-Priority was set, values of LRR_3 for XL are greater than those without IWDPs, while all other values of LRR_1 and LRR_3 are lower than those without IWDPs as shown in Figure 16(c-1) and (c-2).

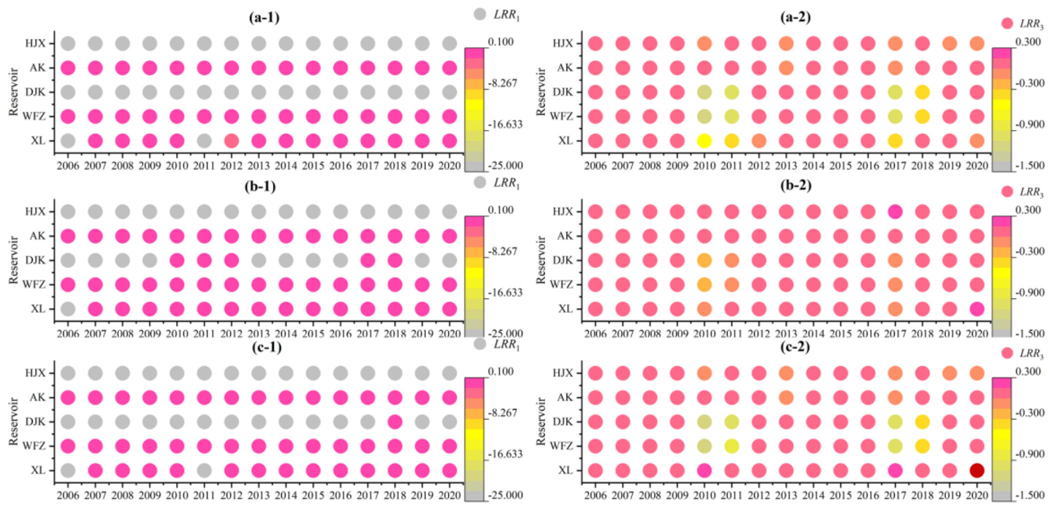

Figure 16. *LRR*$_n$ values when there are different clusters of IWDPs and H-Priority was set at the annual scale: (a-1) and (a-2) are *LRR*$_2$ and *LRR*$_3$ when there was only water donation (i.e., between $S_{2\text{-}1\text{-}2\text{-}c}$ and $S_{1\text{-}0\text{-}4\text{-}c}$), (b-1) and (b-2) are those when there was only water receiving (i.e., between $S_{2\text{-}2\text{-}2\text{-}c}$ and $S_{1\text{-}0\text{-}4\text{-}c}$), (c-1) and (c-2) are those when there were both donation and receiving (i.e., between $S_{2\text{-}3\text{-}2\text{-}c}$ and $S_{1\text{-}0\text{-}4\text{-}c}$).

If there was only water donation and E-Priority was set, more negative values of LRR_1 for HJX, DJK and XL are found in low flow years as shown in Figure 17 (a-1) and all of these values are lower than those without IWDPs as shown in Figure 10 (c-1). All five reservoirs get more smaller values of LRR_2 and only value of LRR_2 for XL in 2007 and 2008 increase as shown in Figure 17 (a-2) because of the reduced spilled water with water donation. If there was only water receiving and E-Priority was set, there are no change on values of LRR_1 for five reservoirs as shown in Figure 17 (b-1), so water receiving has minimal impact on feedbacks of E on S. values of LRR_2 for DJK, WFZ and XL are greater than those without IWDPs. If there were both water donation and receiving and H-Priority was set, values of LRR_1 for HJX, DJK and XL are found to be similar to those with only water donation. Values of LRR_2 for DJK and WFZ are greater than those with only water receiving.

Therefore, water donation has negative impacts on the negative feedbacks between S and H, on the negative feedbacks between S and E, and on the positive feedbacks between H and E, while receiving water has positive impacts on these feedbacks across different time scales. Compared with the values of LRR_n at monthly scale, the values of LRR_n at seasonal and annual scales are stable and changes can be found in low flow periods.

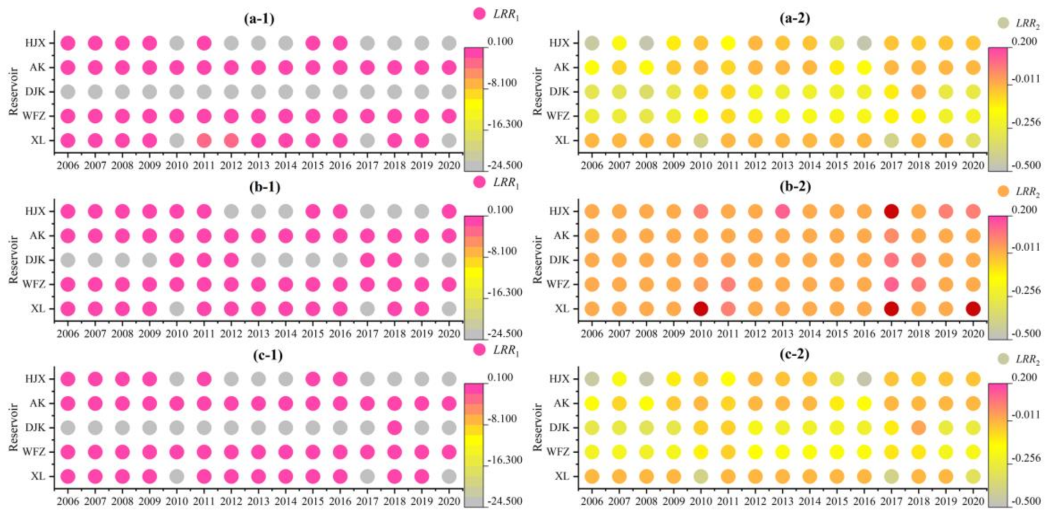

Figure 17. LRR_n values when there are different clusters of IWDPs and E-Priority was set at the annual scale: (a-1) and (a-2) are LRR_2 and LRR_3 when there was only water donation (i.e., between $S_{2\text{-}1\text{-}3\text{-}c}$ and $S_{1\text{-}0\text{-}4\text{-}c}$), (b-1) and (b-2) are those when there was only water receiving (i.e., between $S_{2\text{-}2\text{-}3\text{-}c}$ and $S_{1\text{-}0\text{-}4\text{-}c}$), (c-1) and (c-2) are those when there were both donation and receiving (i.e., between $S_{2\text{-}3\text{-}3\text{-}c}$ and $S_{1\text{-}0\text{-}4\text{-}c}$).

4.4 Responses of the three components with IWDPs

To identify the impacts of IWDPs on S, H and E components in a reservoirs group, differences between indexes without IWDPs and with IWDPs (i.e., $S_{2\text{-}3\text{-}4\text{-}c}$ and $S_{1\text{-}0\text{-}4\text{-}c}$) are determined. Negative values of LRR_1 for five reservoirs are found in all months, mean values of LRR_1 for five reservoirs are -0.002, -0.002, -5.540, -0.218 and -0.013 as shown in Figure 18 (a). It is found that values of LRR_1 for DJK are significantly smaller than those for other reservoirs. These IWDPs have notable negative impacts on the water supply from DJK, which is consistent with the founding by Ouyang et al. (2018). There are some positive values of LRR_1 for five reservoirs are found in abundant water months. Mean values of LRR_2 for five reservoirs are -0.464, -0.149, -0.320, -0.259 and -0.025 as shown in Figure 18 (b). So IWDPs have negative impacts on hydropower generation, but they have positive impacts on H in abundant water months. Many studies have highlighted the negative impacts of IWDPs on hydropower generation (Yang, et al., 2023), but the positive impacts are less frequently discussed. Positive values of LRR_3 are found in XL and negative values of LRR_3 are found in HJX, AK, DJK and WFZ in all months, mean values of LRR_3 for five reservoirs are -5.208, -0.747, -0.758, -0.473 and 0.428 as shown in Figure 18 (c). With the water donation for the Han-to-Wei Water Diversion Project, the Middle Route of the South-to-North Water Diversion Project and the Northern Hubei Water Resources Allocation Project, multiple algal bloom events occurred in the downstream of HRB (Tian et al., 2022), and the water donation had a significant negative impact on the environment conservation of the basin. Water receiving from the Three Gorges Reservoir to Hanjiang River are not compensate for all their negative impacts, and water receiving from the Changjiang-to-Hanjiang River Water Diversion Project benefits environment conservation for XL. Therefore, S, H and E for all reservoirs are impacted by IWDPs. Water donation results in a reduction of available water for water donation areas, so it has negative impacts on water supply, hydropower generation and environment conservation form these areas, while water receiving has positive impacts on S, H and E for water receiving areas because of increased available water.

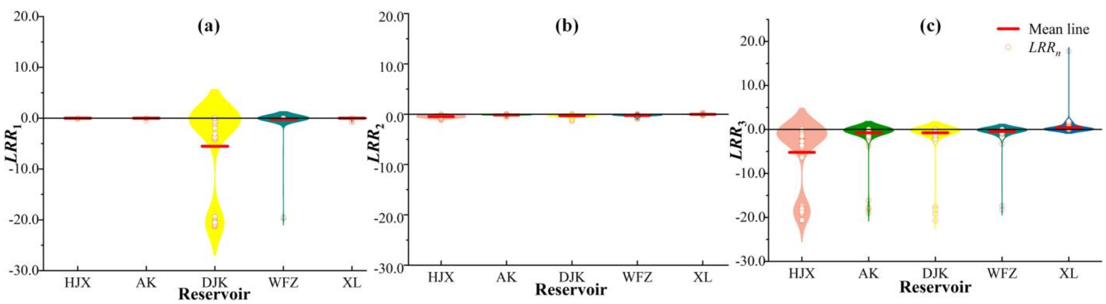

Figure 18. the differences of indexes (i.e., (a) LRR_1, (b) LRR_2, (c) LRR_3 for log response ratio of the S, H, and E component) between $S_{2\text{-}3\text{-}4\text{-}c}$ and $S_{1\text{-}0\text{-}4\text{-}c}$ at the monthly scale.

"A framework was proposed to address the different impacts of IWDPs on the dynamic SHE nexus across the multiple temporal and spatial scales in reservoirs group with different priority functions, and to explore collaborative states in feedback loops. The HRB was taken as case study to verify the feasibility and reliability of this framework. Negative feedbacks can be found between S and H, and between S and E while positive feedbacks can be found between H and E in a reservoirs group without IWDPs. The negative feedbacks of S on H and the positive feedbacks of E on H are weakened or even broken in abundant water periods. All feedback loops are strengthened in low flow periods accompanied by their greater or smaller values of LRR_n than other periods. If there was only water donation, all values of LRR_n for the reservoirs are lower than those without IWDPs, while all values of LRR_n for reservoirs are greater than those without IWDPs. Water donation has negative impacts on the negative feedbacks between S and H, on the negative feedbacks between S and E, and on the positive feedbacks between H and E. While water receiving has positive impacts on these feedbacks. Less positive feedbacks are found with IWDPs than without them. Feedback loops of SHE nexus exhibit intrinsic similarity and stability across different time scales. The impact of reservoir operation and regulation on SHE nexus are clearer at the monthly scale. The seasonal scale offers the variations in periodic feedback loops. And the annual scale offers inter-annual and spatial trends of the SHE nexus from a macro perspective. Feedback loops in reservoirs with regulation function (e.g., AK and DJK) can remain stable under the varying inflow conditions at monthly scale. The positive feedbacks between H and E are weakened or even turn to be negative in the small installed hydropower generation capacity reservoirs (e.g., the XL reservoir) even in abundant water periods. Feedback loops for downstream reservoirs are influenced by their upstream reservoirs, especially in low flow periods. Thus, water donation or regional water supply can be increasing in abundant water periods to reduce spilled water and increase hydropower generation efficiency. In dry periods, it is necessary to consider the priority order of S, H, and E, and determine water utilization threshold for each component to maximize the benefits."

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