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System Dynamics-Multiple Objective Optimization Model for Water Resource Management: A Case Study in Jiaxing City, China

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Supplementary Material for A System Dynamics-Multiple Objective Optimization Model for Water Resource Management: A Case Study in Jiaxing City, China

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Table S1. SD equations in Vensim (High inflow level).

INITIAL TIME = 2011 Units: Year
FINAL TIME = 2035 Units: Year
TIME STEP = 1 Units: Year

1. water shortage rate=SIMULTANEOUS (water shortage rate+((water demand-water supply)/water demand*100-water shortage rate)*0.2, 0)
   Units: Dmnl
2. water supply=diversion project supply + reclaimed water supply + surface water supply
   Units: m^3
3. water demand=agriculture water demand + domestic water demand + industrial water demand+ environmental water demand
   Units: m^3
4. surface water supply= (local surface water resources + transit water resources) * "# utilization rate of surface water"/100
   Units: m^3
5. diversion project supply = WITH LOOKUP (Time, ([(2011,0)-(2035,7.8e+08)], (2011,0), (2017,0),(2018,7.8e+08),(2035,7.8e+08)))
6. Units: m^3
7. reclaimed water supply=wastewater treatment amount * "# utilization rate of reclaimed water"/100
   Units: m^3
8. domestic water demand=rural domestic water demand + urban public water demand + urban domestic water demand
   Units: m^3
9. agriculture water demand=aquaculture water demand + crop production water demand + forest land water demand+ garden water demand + livestock water demand
   Units: m^3
10. industrial water demand="# water use efficiency of industry"*added value of industry
    Units: m^3
11. environmental water demand=greenland area * water quota for greenland
    Units: m^3
12. "# change rate of added value of industry"=change rate of added value of industry*α2
    Units: Dmnl
13. "# change rate of added value of tertiary industry"=change rate of added value of tertiary industry*α2
    Units: Dmnl
14. "# population growth rate"=population growth rate*α2
    Units: Dmnl
15. "# rural domestic water demand per capita"=rural domestic water demand per capita*α1
    Units: m^3/yuan
16. "# utilization rate of reclaimed water"=utilization rate of reclaimed water*α3
    Units: Dmnl
17. "# utilization rate of surface water"=utilization rate of surface water*α3
    Units: Dmnl
18. "# urban domestic water demand per capita"=urban domestic water demand per capita*α1
    Units: m^3/yuan
19. "# water quota for dry land"=water quota for dry land*α1

Units: m^3/mu

20. "# water quota for paddy field"=water quota for paddy field*α1
    Units: m^3/mu
21. "# water use efficiency of industry"=water use efficiency of industry*α1
    Units: m^3/yuan
22. "# water use efficiency of tertiary industry"=water use efficiency of tertiary industry*α1
    Units: m^3/yuan
23. added value of construction industry=GDP * proportion of secondary industry/100-added value of industry
    Units: yuan
24. added value of industry= INTEG (change in added value of industry,1.37367e+11)
    Units: yuan
25. added value of tertiary industry= INTEG (change in added value of the tertiary industry, 1.02821e+11)
    Units: yuan
26. aquaculture water demand=fish pond area * water quota for aquaculture
    Units: m^3
27. change in added value of industry="# change rate of added value of industry"*added value of industry/100
    Units: yuan
28. change in added value of the tertiary industry="# change rate of added value of tertiary industry"*added value of tertiary industry /100
    Units: yuan
29. change rate of added value of industry = WITH LOOKUP (Time, ([(2011,0) - (2035,20)], (2011,0), (2012,8.94), (2015,7), (2016,7.5), (2017,8.5), (2020,3.64), (2025,2.55), (2035,3.35)))
    Units: Dmnl
30. change rate of added value of tertiary industry = WITH LOOKUP (Time, ([(2011,0)-(2035,20)],(2011,0),(2012,14.57),(2020,11.52),(2024.87,8.3),(2035,6.32)))
    Units: Dmnl
31. construction industry water demand=added value of construction industry * water use efficiency of construction industry
    Units: m^3
32. crop production water demand="# water quota for dry land"*dry land area+"# water quota for paddy field"*paddy field area
    Units: m^3
33. discharge coefficient of domestic sewage=0.64
    Units: Dmnl
34. discharge coefficient of industrial wastewater=0.6
    Units: Dmnl
35. domestic sewage discharge=domestic water demand * discharge coefficient of domestic sewage
    Units: m^3
36. domestic sewage processing ratio = WITH LOOKUP (Time, ([(2011,70)-(2035,100)], (2011,78.51),(2017,96.26),(2020,98),(2025,100),(2035,100)))
    Units: Dmnl
37. dry land area = WITH LOOKUP (Time, ([(2011,300000)-(2035,500000)], (2011,499800), (2012,490500),(2015,340056) ,(2016,345600),(2017,345800),(2020,341800),(2035,341800)))
    Units: mu
38. fish pond area = WITH LOOKUP (Time, ([(2011,100000)-(2035,300000)], (2011,203300),

(2012,200800),(2013,208000),(2014,204400),(2015,203000),(2016,201800),(2017,198200),(2020,192000),(2025,180900),(2035,169800)))
Units: mu

39. forest land area = WITH LOOKUP (Time, ([(2011,0)-(2035,500000)], (2011,291600),(2012,301200),(2013,370500),(2014,384300),(2015,453000),(2016,21500),(2035,21500)))
Units: mu
40. forest land water demand=forest land area * water quota for forest land
Units: m^3
41. garden area = WITH LOOKUP (Time, ([(2011,0)-(2035,50000)], (2011,6500),(2012,5400), (2013,7000),(2014,6200),(2015,5000),(2016,43700),(2035,43700)))
Units: mu
42. garden water demand=garden area * water quota for garden
Units: m^3
43. GDP=added value of tertiary industry/proportion of tertiary industry * 100
Units: yuan
44. greenland area = WITH LOOKUP (Time, ([(2011,3000)-(2035,6000)], (2011,3151.37),(2012,3394.93),(2013,3599.4),(2014,3787.56),(2015,4034.87),(2016,4144.34),(2017,4474.15),(2020,4500),(2025,4800),(2035,5000)))
Units: ha
45. industrial wastewater discharge=industrial water demand * discharge coefficient of industrial wastewater
Units: m^3
46. industrial wastewater processing ratio = WITH LOOKUP (Time, ([(2011,0)-(2035,100)], (2011,66.63),(2014,87.33),(2020,92),(2025,94),(2035,95)))
Units: Dmnl
47. large livestock amount = WITH LOOKUP (Time, ([(2011,0)-(2035,5000)], (2011,4300),(2012,4675),(2013,2434),(2014,2007),(2016,1327),(2017,1275),(2020,1164),(2025,1107),(2035,1107)))
Units: head
48. livestock water demand=large livestock amount * water quota for large livestock + small livestock amount* water quota for small livestock
Units: m^3
49. local surface water resources = WITH LOOKUP (Time, ([(2011,0)-(2035,4e+09)], (2011,1.23e+09),(2012,3.283e+09),(2013,1.848e+09),(2014,2.033e+09),(2015,3.472e+09),(2016,3.643e+09),(2017,2.39e+09),(2018,2.154e+09),(2035,2.154e+09)))
Units: m^3
50. paddy field area = WITH LOOKUP (Time, ([(2011,2e+06)-(2035,3e+06)],(2011,2.612e+06),(2012,2.521e+06),(2013,2.369e+06),(2015,2.237e+06),(2016,2.243e+06),(2017,2.243e+06),(2020,2.287e+06),(2035,2.287e+06)))
Units: mu
51. population growth="# population growth rate" * total population/1000
Units: person
52. population growth rate = WITH LOOKUP (Time, ([(2011,0)-(2035,20)], (2011,0),(2012,2.8691),(2013,3.081),(2014,2.6327),(2015,3.2823),(2016,6.325),(2017,9.1027),(2020,14),(2025,13),(2035,11.5)))
Units: Dmnl
53. proportion of secondary industry = WITH LOOKUP (Time, ([(2011,0)-(2035,60)],(2011,57.58),(2012,56.18),(2013,54.86),(2014,54.02),(2015,52.6),(2016,50.84),(2017,53.02),(2020,48.2),(2025,42.8),(2035,37.8)))
Units: Dmnl
54. proportion of tertiary industry = WITH LOOKUP (Time, ([(2011,0)-(2035,60)],(2011,36.95),(2012,38.62),(2013,40.2),(2014,41.65),(2015,43.41),(2016,45.34),(2017,43.88),(2020,49.4),(2025,55),(2035,60)))

Units: Dmnl

55. rural domestic water demand="# rural domestic water demand per capita"*rural population
    Units: m^3
56. rural domestic water demand per capita = WITH LOOKUP (Time, ([(2011,30)-(2035,50)],(2011,43.45),(2012,39.66),(2013,41.08),(2014,42.69),(2015,43.68),(2016,45.36),(2017,47.54),(2020,49.28),(2025,47.45),(2035,45.63)))
    Units: m^3/person
57. rural population=total population - urban population
    Units: person
58. small livestock amount = WITH LOOKUP (Time, ([(2011,0)-(2035,4e+06)],(2011,3.6383e+06),(2012,3.3546e+06),(2013,2.5713e+06),(2014,1.411e+06),(2015,894000),(2016,832900),(2017,637800),(2020,300000),(2025,500000),(2035,600000)))
    Units: head
59. tertiary industry water demand="# water use efficiency of tertiary industry"*added value of tertiary industry
    Units: m^3
60. total population= INTEG (population growth, 4.531e+06)
    Units: person
61. transit water resources = WITH LOOKUP (Time, ([(2011,4e+09)-(2035,8e+09)],(2011,6.711e+09),(2012,7.382e+09),(2013,5.929e+09),(2014,5.966e+09),(2015,6.777e+09),(2016,7.58e+09),(2017,5.039e+09),(2018,6.121e+09),(2035,6.121e+09)))
    Units: m^3
62. utilization rate of reclaimed water = WITH LOOKUP (Time, ([(2011,0)-(2035,50)],(2011,0.78),(2015,1.14),(2016,2.8),(2017,3),(2020, 8),(2025,10),(2035,15)))
    Units: Dmnl
63. urban domestic water demand="# urban domestic water demand per capita"*urban population
    Units: m^3
64. urban domestic water demand per capita = WITH LOOKUP (Time, ([(2011,40)-(2035,60)],(2011,48.77),(2012,46.63),(2013,45.6),(2014,47.79),(2015,49.93),(2016,49.14),(2017,50.45),(2020,51.1),(2025,49.28),(2035,47.45)))
    Units: m^3/person
65. urban population=total population * urbanization rate/100
    Units: person
66. urban public water demand=tertiary industry water demand + construction industry water demand
    Units: m^3
67. urbanization rate = WITH LOOKUP (Time, ([(2011,0)-(2035,90)],(2011,53.46),(2012,55.3),(2013,57.1),(2014,59.2),(2015,60.9),(2016,62.9),(2017,64.54),(2020,68),(2025,74),(2035,83)))
    Units: Dmnl
68. utilization rate of surface water = WITH LOOKUP (Time, ([(2011,0)-(2035,100)],(2011,24.65),(2012,17.77),(2013,26.01),(2014,24.18),(2015,18.5),(2016,16.76),(2017,25.35),(2018,20),(2035,20)))
    Units: Dmnl
69. wastewater treatment amount= (domestic sewage discharge * domestic sewage processing ratio + industrial wastewater discharge* industrial wastewater processing ratio)/100
    Units: m^3
70. water quota for aquaculture = WITH LOOKUP (Time, ([(2011,0)-(2035,500)],(2011,359.71),(2012,390.29),(2013,379.81),(2014,387.82),(2015,435.12),(2016,332.61),(2017,340.06),(2020,375),(2025,365),(2035,350)))

Units: m^3/mu

71. water quota for dry land = WITH LOOKUP (Time, ([(2011,0)-(2035,300)],(2011,101.06),(2012,92.58),(2013,94.46),(2014,118.45),(2015,88.25),(2016,107.06),(2017,104.77),(2018,118),(2035,118)))
    Units: m^3/mu
72. water quota for forest land = WITH LOOKUP (Time, ([(2011,0)-(2035,200)],(2011,96.16),(2015.99,77.21),(2020,90),(2025,85), (2035,80)))
    Units: m^3/mu
73. water quota for garden = WITH LOOKUP (Time, ([(2011,0)-(2035,100)],(2011,61.54),(2020,60),(2025,58),(2035,55)))
    Units: m^3/mu
74. water quota for greenland = WITH LOOKUP (Time, ([(2011,0)-(2035,30000)],(2011,7161.97),(2012,5947),(2013,6740.02),(2014,6943.78),(2015,7452.53),(2016,9970.22),(2017,9733.69),(2020,10950),(2025, 18250),(2035,29200)))
    Units: m^3/ha
75. water quota for large livestock = WITH LOOKUP (Time, ([(2011,20)-(2035,40)],(2011,29.2),(2020,38.33),(2025,36.5),(2035,32.85)))
    Units: m^3/head
76. water quota for paddy field = WITH LOOKUP (Time, ([(2011,0)-(2035,600)],(2011,348.23),(2012.03,360.782),(2013,418.644),(2014,414.812),(2016,403.331),(2017,393.327),(2018,297),(2035,297)))
    Units: m^3/mu
77. water quota for small livestock = WITH LOOKUP (Time, ([(2011,0)-(2035,40)],(2011,9.125),(2020,10.95),(2025,9.125),(2035,6.57)))
    Units: m^3/head
78. water use efficiency of construction industry = WITH LOOKUP (Time, ([(2011,0.001)-(2035,0.002)],(2011,0.001356),(2012,0.001278),(2013,0.001578),(2014,0.00147),(2015,0.001513),(2016,0.001192),(2017,0.001149),(2020,0.0011),(2025,0.00105),(2035,0.001)))
    Units: m^3/yuan
79. water use efficiency of industry = WITH LOOKUP (Time, ([(2011,0)-(2035,0.004)],(2011,0.00349),(2012,0.003041),(2013,0.00296),(2014,0.002704),(2015,0.0025),(2016,0.002292),(2017,0.0022),(2020,0.002),(2025,0.0018),(2035,0.0016)))
    Units: m^3/yuan
80. α1= 1+IF THEN ELSE(water shortage rate>0, STEP(-SIN(3.14159*water shortage rate*f1/200), 2018) , 0)
    Units: Dmnl
81. α2= 1+IF THEN ELSE(water shortage rate>0, STEP(-SIN(3.14159*water shortage rate*f2/200), 2018) , 0)
    Units: Dmnl
82. α3= 1+IF THEN ELSE(water shortage rate>0, STEP(SIN(3.14159*water shortage rate*f3/200), 2018) , 0)
    Units: Dmnl

Table S2. Observed and predicted values of social-economic parameters of Jiaxing.

Indicators		2017	2020	2025	2035
Natural growth rate (‰)		3.64	4	3.5	3
Mechanical growth rate (‰)		8.35	10	9.5	8.5
Urbanization rate (%)		64.54	68	74	83
Total population (10^4 person)		465.60	479.34	507.93	564.52
Urban population (10^4 person)		300.48	325.95	375.87	468.55
Rural population (10^4 person)		156.12	153.39	132.06	95.97
Irrigated area (10^4 ha)	Paddy field	14.96	15.24	15.24	15.24
	Dry land	2.305	2.279	2.279	2.279
	Forestland	0.1433	0.1433	0.1433	0.1433
	Garden	0.2913	0.2913	0.2913	0.2913
	Fish pond	1.321	1.28	1.206	1.132
	green land	0.4474	0.45	0.48	0.50
Inventory (10^4 head)	Large livestock	0.1275	0.1164	0.1107	0.1107
	Small livestock	63.78	30	45	50
Gross product (10^8 yuan)	Primary industry	135.8	129.84	159.28	269.5
	Industry	2110.4	2349.66	2664.86	3704.42
	Construction industry	207.33	258	433.81	926.11
	Tertiary industry	1926.99	2672.58	3981.95	7350.05
	GDP	4380.52	5410.08	7239.9	12250.08

Table S3. Water quota of each sector in Jiaxing.

Water Sector (units)		2017	2020	2025	2035
Agriculture	Paddy fields (m^3/ha)	5899.5		4455 (High) 5940 (Mid) 6480 (Low)	
	Dry land (m^3/ha)	1572		1770 (High) 2775 (Mid) 3225 (Low)	
	Forestland (m^3/ha)	1240.5	1350	1275	1200
	Garden (m^3/ha)	1000.5	900	870	825
	Fish pond (m^3/ha)	5626.5	5625	5475	5250
	Large livestock (m^3/head)	104.9	100	90	90
	Small livestock (m^3/head)	31.1	25	20	20
Domestic	Urban residents (L/(person·d))	138.2	140	135	130
	Rural residents (L/(person·d))	130.3	135	130	125
	Construction industry ($m^3/10^4$ yuan)	11.5	11	10.5	10
	Tertiary industry ($m^3/10^4$ yuan)	5.4	5.2	5.0	4.8
Industry	Industry ($m^3/10^4$ yuan)	20.5	21	18.9	17.5
Ecology	Urban green space (L/(m^2·d))	2.67	2.04	2.04	2.04

Table S4. Parameter values in objective functions in MOO model.

Cost coefficient y_{ij}*	y_{11}	y_{12}	y_{13}	y_{14}	y_{22}	y_{23}	y_{32}
(yuan/m^3)	0.20	6.10	3.25	0.20	8.20	3.95	2.80
Discharge coefficient	k^d				k^i		
	0.64				0.6		
COD concentration	c^d				c^i		
(mg/L)	103.04				85.07		

* i: water source; 1= surface water, 2 = diversion water, 3 = reclaimed water.
j: water user; 1= agriculture, 2 = industry, 3 = domestic, 4 = environment.

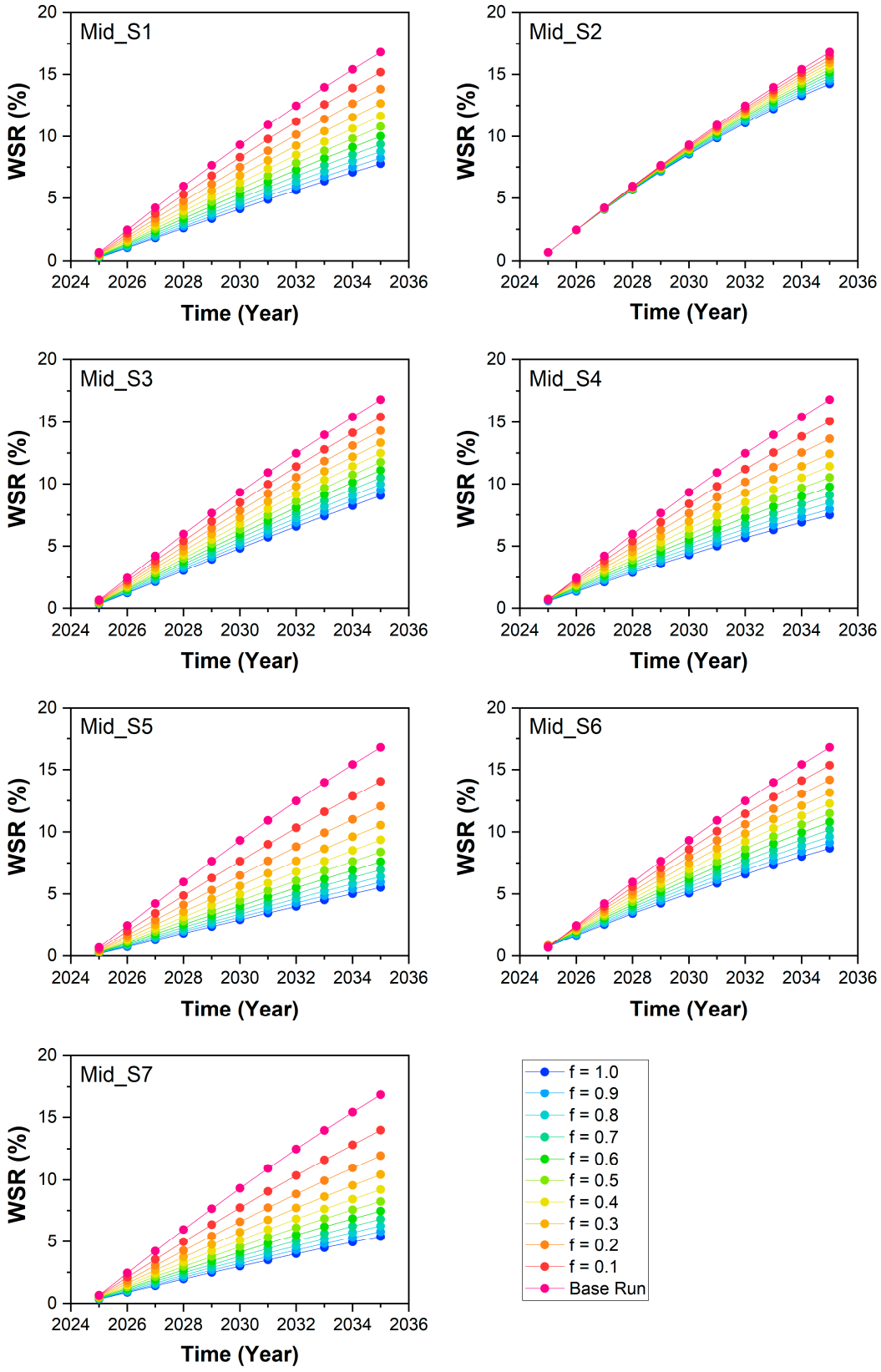


Figure S1. Effect of feedback intensity f (from 0 to 1) on water shortage rates (WSR) for various scenarios at mid inflow level (2025–2035).

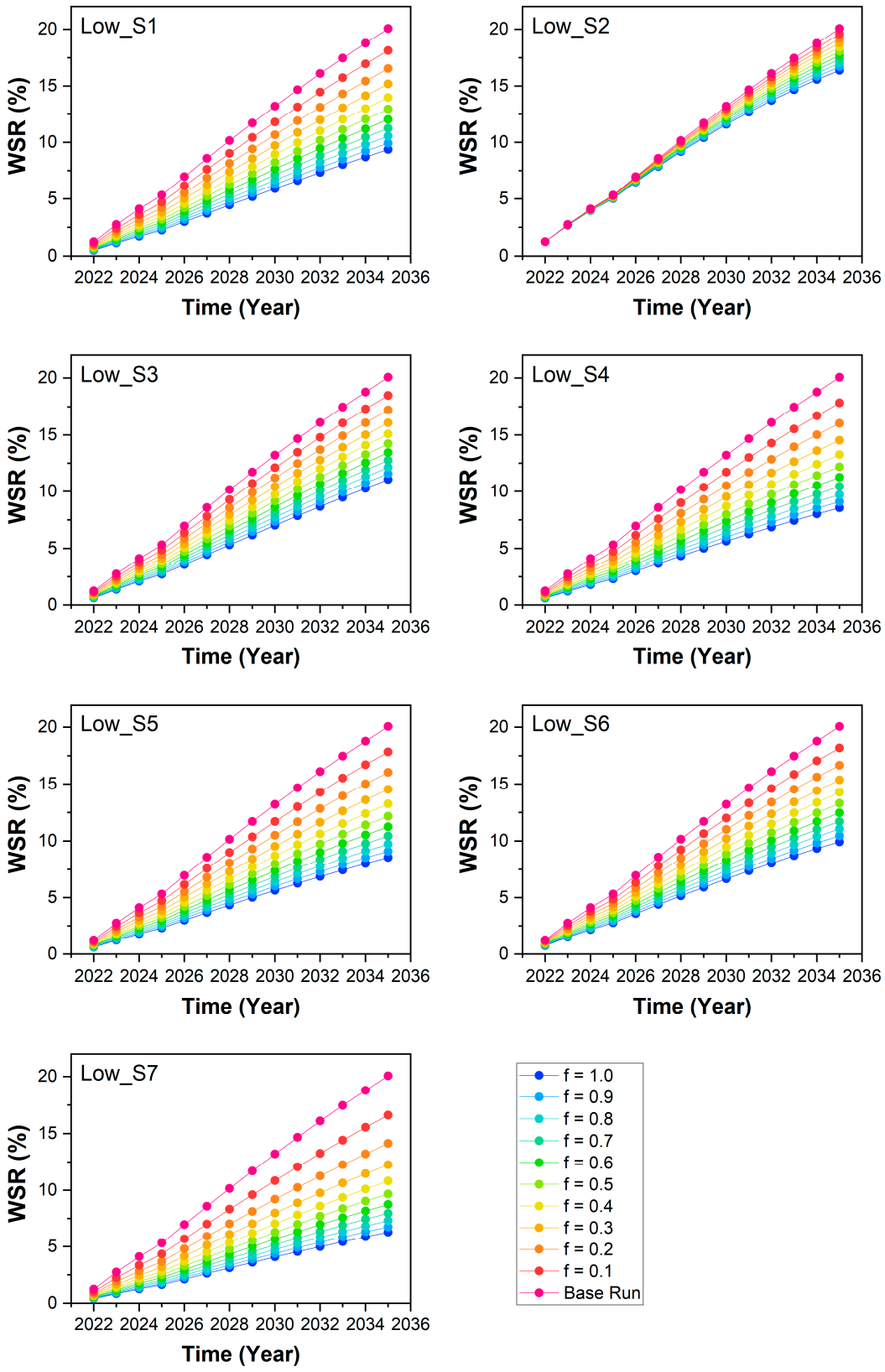


Figure S2. Effect of feedback intensity *f* (from 0 to 1) on WSR for various scenarios at low inflow level (2022–2035).

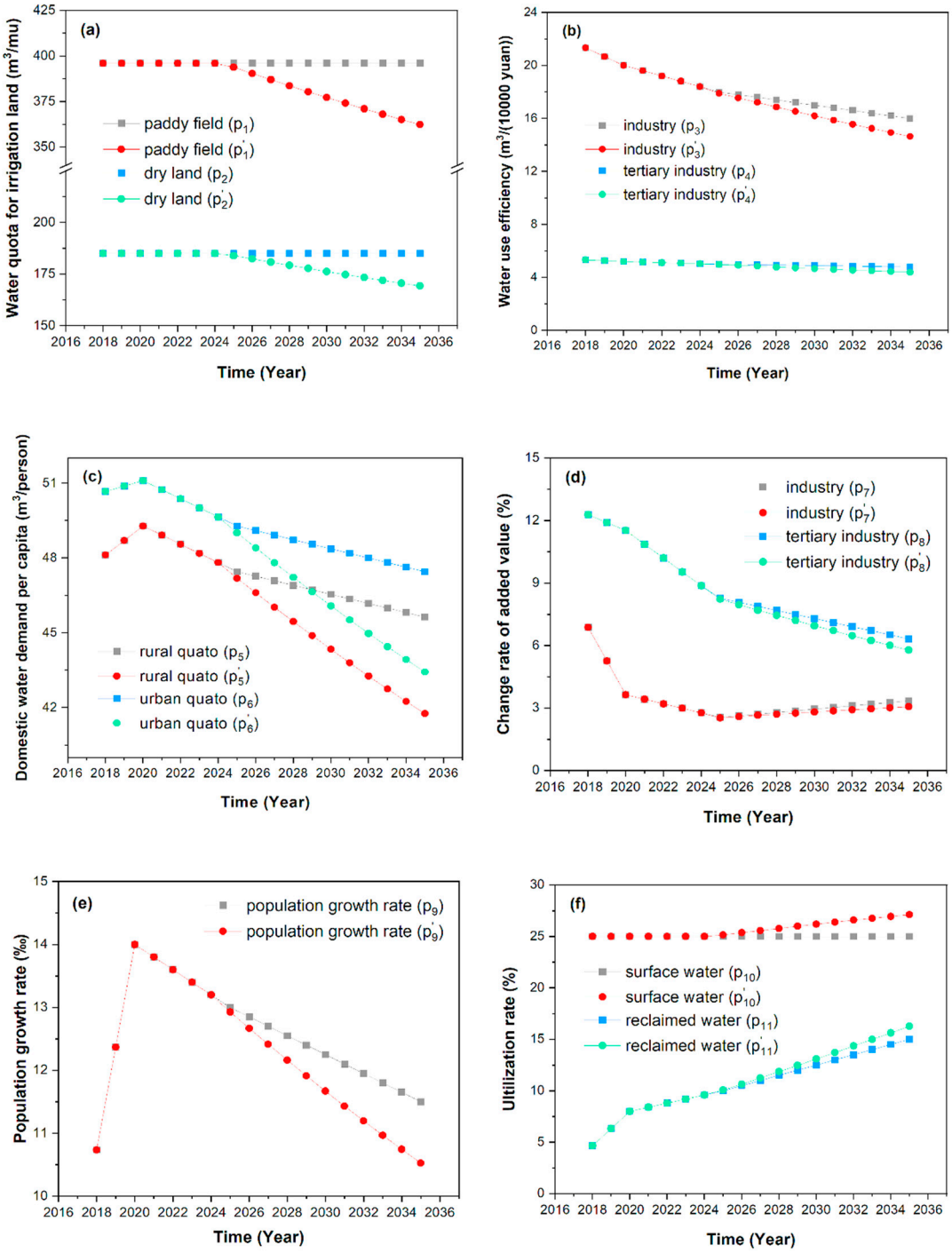


Figure S3. Values of policy adjusted variables in scenario (p_n) and S7 (with f = 1, p'_n) at mid-inflow level.

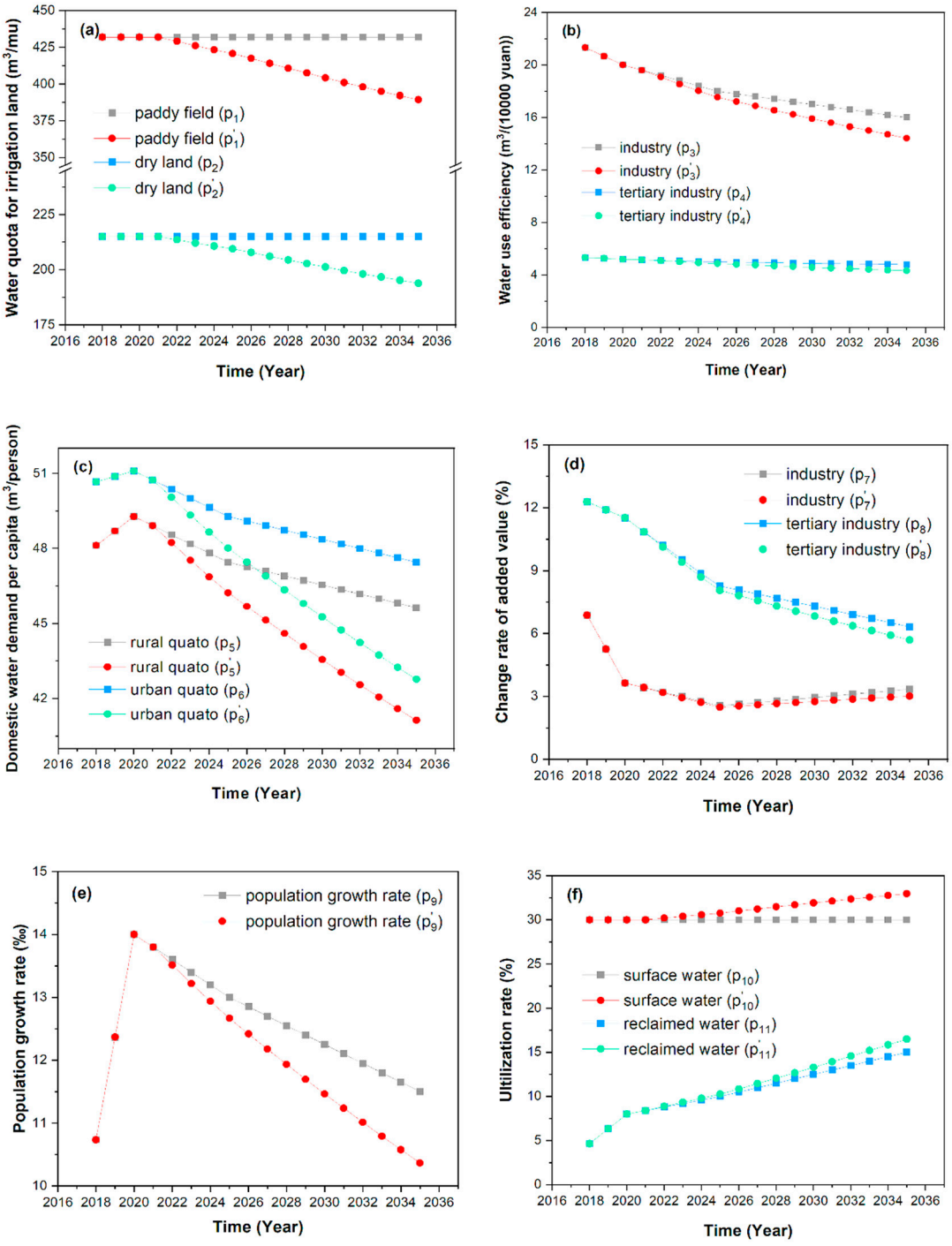


Figure S4. Values of policy adjusted variables in scenario (p_n) and S7 (with f = 1, p'_n) at low-inflow level.

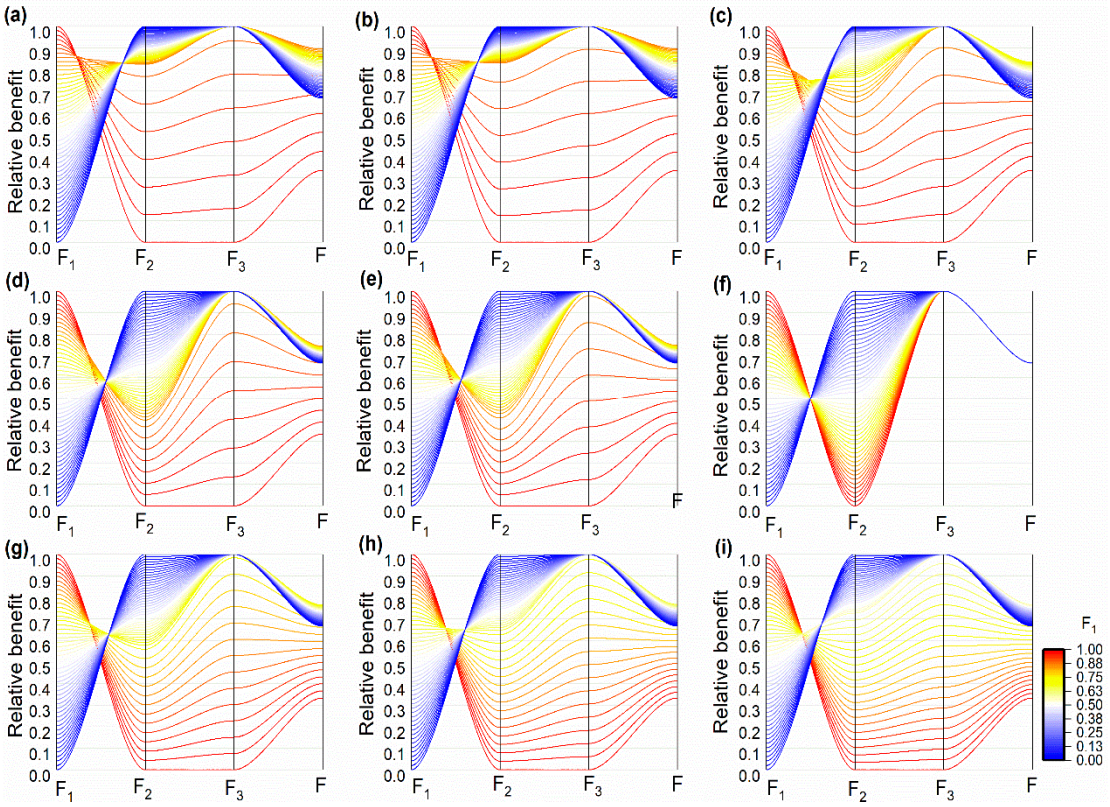


Figure S5. Individual and combined benefits of pareto sets. (**a**) High-2020, (**b**) High-2025, (**c**) High-2035, (**d**) Mid-2020, (**e**) Mid-2025, (**f**) Mid-2035, (**g**) Low-2020, (**h**) Low-2025, (**i**) Low-2035.

The separate benefits and their equal weighted sum of all pareto sets in nine situations showed the same pattern. When the social benefits were relatively optimal (F_1 =1), the economic (F_2) and environmental benefits (F_3) were not. As social benefit gave its way, economic and environmental benefits were improved, and the comprehensive benefit significantly performed better, of which the corresponding expression in the figure was that sparse red curves transited to dense yellow curves. Since then, the environmental benefits remained pretty much the same, the economic benefits can be further optimized but severe water scarcity would occur, resulting the overall benefits to decline. The most reasonable choice was the scheme with a maximum comprehensive benefit rather than any single optimal benefit scheme.