Supplementary material for:

A Hierarchical Hydrological Knowledge-guided Attention Network for Groundwater Depth Prediction: Insights from Multi-regional Model Interpretation

Jing Xu[1*], Yuming Mo[2], Senlin Zhu[1], Chengji Shen[3], Xinli Zhu[4], Chenming Zhang[5], Qihao Jiang[6], Ling Li[7]

1. College of Hydraulic Science and Engineering, Yangzhou University, Yangzhou, China
   Emails: xujing7503@yzu.edu.cn
   slzhu@yzu.edu.cn
2. School of Naval Architecture and Ocean Engineering, Jiangsu University of Science and Technology, Zhenjiang, China
   Email: yumingmo@just.edu.cn
3. Ministry of Education Key Laboratory of Integrated Regulation and Resource Development on Shallow Lakes, Hohai University, Nanjing, China
   Email: c.shen@hhu.edu.cn
4. School of Water Conservancy, North China University of Water Resources and Electric Power, Zhengzhou, China
   Email: zhuxl890@126.com
5. School of Civil Engineering, The University of Queensland, Brisbane, Australia
   Email: chenming.zhang@uq.edu.au
6. Jiangsu Center for Collaborative Innovation in Geographical Information Resource Development and Application, Nanjing Normal University, Nanjing, China
   Email: jiangqih@hotmail.com
7. Key Laboratory of Coastal Environment and Resources of Zhejiang Province (KLaCER), School of Engineering,Westlake University, Hangzhou, China
   Email: liling@westlake.edu.cn

* Corresponding author: Jing Xu (xujing7503@yzu.edu.cn)

This file contains seven tables S1-S7 and seven figures S1-S7.

Table S1. Percentage of land use types within 500m buffer zones for site type classification in the three study regions.

Site code	Cropland	Forest	Grassland	Waters	Artificial surfaces	Site type
			YTMR			
A1	86.0	0.0	0.0	0.0	14.0	agricultural
A2	86.1	0.0	0.0	0.0	13.9	agricultural
A3	64.5	0.0	0.0	0.0	35.5	agricultural
A4	65.6	0.0	0.0	0.0	34.4	agricultural
A5	100.0	0.0	0.0	0.0	0.0	agricultural
A6	69.3	0.0	0.0	0.0	30.7	agricultural
A7	66.9	1.7	4.2	0.0	27.1	agricultural
A8	67.6	0.0	0.0	0.0	32.4	agricultural
A9	77.2	0.0	0.0	0.0	22.8	agricultural
A10	85.8	0.0	0.0	0.0	14.2	agricultural
A11	63.6	0.0	0.0	0.0	36.4	agricultural
A12	99.3	0.0	0.0	0.0	0.7	agricultural
A13	78.4	0.0	0.0	0.0	21.6	agricultural
A14	69.5	1.0	5.3	0.0	24.2	agricultural
N1	0.1	0.5	47.3	0.0	52.1	natural
N2	34.9	0.1	58.3	0.0	6.6	natural
N3	54.9	0.1	3.4	0.0	41.6	natural
N4	55.5	2.2	13.5	0.0	28.8	natural
N5	50.6	0.1	30.4	0.0	18.8	natural
N6	58.9	0.0	0.2	0.0	40.8	natural
N7	46.6	0.0	0.0	0.0	53.4	natural
N8	8.4	3.1	35.2	0.0	53.3	natural
N9	8.5	6.3	9.6	21.2	54.5	natural
N10	39.5	0.5	4.0	0.0	56.0	natural
N11	41.8	8.6	26.6	0.0	23.0	natural
U1	0.0	0.0	0.0	3.0	97.0	urban
U2	34.9	0.0	0.0	0.0	65.1	urban
U3	10.9	0.0	10.3	17.6	61.2	urban
U4	19.2	0.6	10.6	0.0	69.6	urban
U5	0.3	0.0	0.8	0.0	98.9	urban
U6	31.6	1.9	6.3	0.0	60.2	urban
U7	1.6	0.0	23.2	0.0	75.2	urban
			NCP			
A1	66.7	0.0	0.0	0.0	33.3	agricultural
A2	78.0	0.0	0.0	0.0	22.0	agricultural
A3	91.6	0.0	0.0	0.0	8.4	agricultural

A4	94.8	1.5	2.3	1.4	0.0	agricultural
A5	100.0	0.0	0.0	0.0	0.0	agricultural
A6	82.7	0.0	0.1	0.0	17.2	agricultural
A7	71.6	0.0	0.0	0.0	28.4	agricultural
A8	100.0	0.0	0.0	0.0	0.0	agricultural
A9	95.4	0.0	0.0	0.0	4.6	agricultural
A10	100.0	0.0	0.0	0.0	0.0	agricultural
A11	100.0	0.0	0.0	0.0	0.0	agricultural
A12	70.4	0.0	0.0	0.0	29.6	agricultural
A13	99.8	0.0	0.0	0.0	0.2	agricultural
A14	65.0	0.0	0.0	0.0	35.0	agricultural
A15	92.7	0.0	0.0	0.0	7.3	agricultural
A16	66.7	0.0	0.0	0.0	33.3	agricultural
A17	90.5	0.0	0.0	0.0	9.5	agricultural
A18	100.0	0.0	0.0	0.0	0.0	agricultural
A19	100.0	0.0	0.0	0.0	0.0	agricultural
N1	52.3	0.0	0.0	0.0	47.7	natural
N2	48.7	0.0	0.0	0.0	51.3	natural
N3	57.3	0.0	0.0	0.0	42.7	natural
N4	53.4	0.0	0.0	0.0	46.6	natural
N5	44.4	0.0	0.0	0.0	55.6	natural
U1	38.2	0.0	0.0	0.0	61.8	urban
U2	34.9	0.0	0.0	0.0	65.1	urban
U3	0.5	0.0	0.0	0.0	99.5	urban
U4	16.4	0.0	0.0	0.0	83.6	urban
U5	1.3	0.0	0.0	0.0	98.7	urban
U6	31.5	0.0	0.0	0.0	68.5	urban
U7	36.7	0.0	0.0	0.0	63.3	urban
U8	33.0	0.0	0.0	0.0	67.0	urban
			NJP			
A1	60.5	0.0	0.0	0.0	39.5	agricultural
A2	81.3	0.0	0.0	0.0	18.7	agricultural
A3	89.5	0.0	0.0	0.0	10.5	agricultural
A4	92.8	0.0	0.0	0.0	7.2	agricultural
A5	65.3	0.0	0.0	0.0	34.7	agricultural
A6	98.8	0.0	0.0	0.0	1.2	agricultural
A7	79.8	0.0	0.0	0.5	19.7	agricultural
A8	81.5	0.0	0.0	0.0	18.5	agricultural
A9	94.5	0.0	0.0	0.0	5.5	agricultural
A10	100.0	0.0	0.0	0.0	0.0	agricultural
A11	62.4	0.0	0.0	3.3	34.3	agricultural
A12	100.0	0.0	0.0	0.0	0.0	agricultural
A13	73.6	0.0	0.0	0.0	26.4	agricultural

A14	76.3	0.0	0.0	4.9	18.8	agricultural
A15	100.0	0.0	0.0	0.0	0.0	agricultural
A16	76.3	0.0	0.0	0.0	23.7	agricultural
A17	72.8	0.0	0.0	0.0	27.2	agricultural
A18	71.0	0.0	0.0	0.0	29.0	agricultural
A19	73.4	0.0	0.0	0.0	26.6	agricultural
A20	100.0	0.0	0.0	0.0	0.0	agricultural
A21	84.9	0.0	0.0	0.4	14.8	agricultural
A22	77.1	0.0	0.0	0.0	22.9	agricultural
A23	60.4	0.0	0.0	0.0	39.6	agricultural
N1	58.8	0.0	0.0	0.0	41.2	natural
N2	41.8	0.0	0.0	0.0	58.2	natural
N3	44.4	0.0	0.0	0.0	55.6	natural
N4	42.2	0.0	0.0	1.4	56.4	natural
N5	47.8	0.0	0.0	0.4	51.8	natural
N6	46.1	0.0	0.6	0.9	52.4	natural
N7	24.7	0.0	0.1	30.1	45.1	natural
N8	35.1	0.0	0.0	5.2	59.8	natural
N9	39.7	0.0	0.0	19.7	40.6	natural
N10	43.5	0.0	0.0	0.0	56.5	natural
N11	45.0	0.0	0.0	8.9	46.1	natural
N12	49.3	0.0	0.0	0.0	50.7	natural
N13	40.8	0.0	0.6	36.3	22.3	natural
N14	55.1	0.0	0.0	0.0	44.9	natural
N15	44.5	0.0	0.0	0.0	55.5	natural
N16	41.9	0.0	0.0	2.9	55.2	natural
N17	47.8	0.0	1.2	49.9	1.1	natural
U1	0.0	0.0	0.0	0.0	100.0	urban
U2	1.3	0.0	0.0	0.0	98.7	urban
U3	13.1	0.0	0.0	0.0	86.9	urban
U4	11.6	0.0	0.0	0.0	88.4	urban
U5	35.7	0.0	0.0	0.0	64.3	urban
U6	0.0	0.0	0.0	0.0	100.0	urban
U7	22.1	0.0	0.0	8.7	69.3	urban
U8	5.4	0.0	0.0	0.0	94.6	urban
U9	7.1	0.0	0.0	0.0	93.0	urban
U10	2.4	0.0	0.0	0.0	97.7	urban
U11	0.5	0.0	0.0	0.0	99.5	urban
U12	31.3	0.0	0.0	0.0	68.7	urban
U13	24.5	0.0	1.5	0.0	74.0	urban
U14	0.0	0.0	0.0	0.0	100.0	urban
U15	35.6	0.0	0.0	0.0	64.4	urban
U16	15.9	0.0	0.0	0.0	84.2	urban

U17	31.7	0.0	0.0	0.0	68.4	urban
U18	5.2	0.0	0.0	0.0	94.9	urban
U19	14.8	0.0	0.0	11.1	74.1	urban
U20	9.0	0.0	0.0	19.4	71.6	urban
U21	0.0	0.0	0.0	0.0	100.0	urban
U22	13.8	0.0	0.0	0.0	86.2	urban
U23	26.1	0.0	0.0	1.1	72.9	urban
U24	2.5	0.0	0.0	0.0	97.5	urban

Table S2. Percentage of land use types within multi-scale buffer zones (1000m, 2000m, and 3000m) across the three study regions.

	NJP	NCP	YTMR
Cropland in 1000m buffer (%)	54.1±26.3	65.1±23.9	50.2±28.4
Forest in 1000m buffer (%)	0	0.4±2.3	2.1±3.8
Grassland in 1000m buffer (%)	0.2±1.0	0.1±0.4	14.9±18.0
Waters in 1000m buffer (%)	5.0±12.1	0.1±0.6	1.99±4.4
Artificial surface in 1000m buffer (%)	40.5±25.7	34.1±24.3	30.7±19.8
Cropland in 2000m buffer (%)	61.6±21.9	65.2±21.6	54.2±31.1
Forest in 2000m buffer (%)	0.2±1.6	0.4±2.4	3.6±5.8
Grassland in 2000m buffer (%)	0.2±0.5	0.4±1.5	19.1±20.2
Waters in 2000m buffer (%)	5.9±13.5	0.1±0.2	2.1±5.6
Artificial surface in 2000m buffer (%)	32.0±21.0	33.7±22.0	20.7±15.3
Cropland in 3000m buffer (%)	64.9±20.7	65.5±19.4	54.2±30.6
Forest in 3000m buffer (%)	0.3±2.3	0.8±4.8	4.1±6.1
Grassland in 3000m buffer (%)	0.2±0.6	0.4±1.5	22.3±21.0
Waters in 3000m buffer (%)	6.6±13.4	0.1±0.1	1.8±4.7
Artificial surface in 3000m buffer (%)	27.8±19.2	33.0±19.9	17.4±12.9

Table S3. Predefined encoder weights for different site types in the adaptive fusion mechanism.

Encoder type	Agricultural sites	Natural sites	Urban sites
Historical encoder	0.25	0.30	0.20
Meteorological encoder	0.35	0.40	0.20
Geographical encoder	0.15	0.25	0.20
Human activity encoder	0.25	0.05	0.40

Table S4. Summary of datasets in the Lower Yangtze River Plain (LYRP).

Site type	Agricultural	Natural	Urban
Record number	25564	12782	25564
Site numbers	14	7	14
Groundwater depth (m)	7.67±6.39	6.10±6.68	8.98±3.47
Rainfall (mm/day)	3.24±8.47	3.25±8.34	3.46±9.20
Average temperature (℃)	16.02±9.32	15.59±9.48	16.54±9.36
Maximum temperature (℃)	19.92±9.58	20.15±9.69	20.55±9.65
Minimum temperature (℃)	12.87±9.45	11.92±9.73	13.33±9.40
Elevation (m)	4.50±2.32	2.71±2.05	3.71±1.44
Slope (º)	0.65±0.32	0.78±0.36	0.57±0.29
Watershed numbers	2	3	3
Aquifer types	2	1	1
Distance to the nearest river (m)	392.93±333.42	167.00±105.21	297.43±236.46
Population density (capita/km^2)	840.21±207.00	1056.65±186.57	1331.71±560.13
GDP (10^8 yuan)	2378.19±2386.78	2398.74±2438.94	2618.81±1989.58
Primary industry GDP (10^8 yuan)	82.26±35.30	64.18±45.68	51.75±38.36
Secondary industry GDP (10^8 yuan)	1094.48±1159.93	1158.60±1166.22	1281.50±997.98
Tertiary industry GDP (10^8 yuan)	1131.53±1231.01	1146.42±1255.29	1256.64±998.89
Domestic water (L/(capita·d))	142.65±33.15	147.84±25.90	201.78±70.21
Industrial water (m^3/(10^4 yuan))	22.23±8.50	17.43±10.68	28.65±6.83
Irrigation water (m^3/mu)	350.58±82.06	422.51±89.88	323.14±64.77
Cropland in 500m buffer (%)	80.33±14.50	51.03±6.08	11.13±11.92
Forest in 500m buffer (%)	0.02±0.06	0	0
Grassland in 500m buffer (%)	0	0	0.09±0.28
Waters in 500m buffer (%)	0.45±1.12	4.69±6.97	1.78±3.69

Artificial surface in 500m buffer (%)	19.21±14.87	44.28±9.16	87.00±12.32

Table S5. Performance comparison between HHA-Net and baseline models across agricultural, natural, and urban sites in the Lower Yangtze River Plain (LYRP).

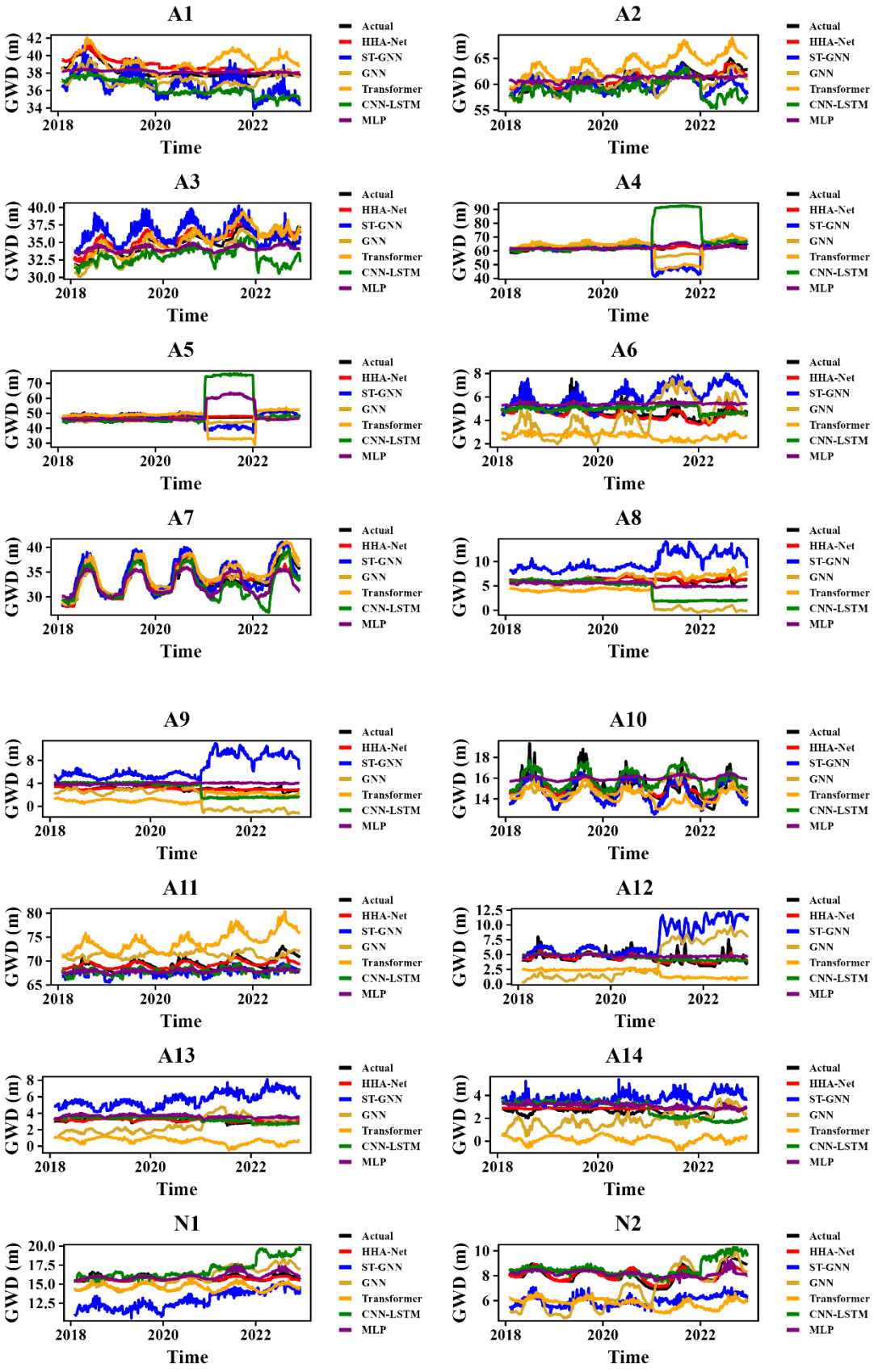
		Agricultural sites				Natural sites				Urban sites			
		MAPE(%)	RMSE	NSE	R^2	MAPE(%)	RMSE	NSE	R^2	MAPE(%)	RMSE	NSE	R^2
LYRP	GNN	5.003	0.250	-0.230	0.696	4.190	0.284	0.407	0.750	2.455	0.2444	0.879	0.927
	CNN_LSTM	6.678	0.303	-0.227	0.521	6.504	0.355	-1.00	0.466	3.560	0.334	0.657	0.869
	MLP	4.962	0.294	0.231	0.565	5.404	0.316	-0.261	0.609	3.802	0.382	0.806	0.889
	ST_GNN	6.235	**0.226**	-0.491	0.617	3.716	**0.163**	0.267	0.750	**1.651**	**0.157**	0.913	0.956
	Transformer	17.019	0.599	-6.471	0.501	14.213	0.624	-4.978	0.526	4.244	0.364	0.469	0.887
	HHA-Net	**4.923**	0.232	**0.330**	**0.704**	**3.559**	0.266	**0.619**	**0.858**	2.256	0.232	**0.919**	**0.961**

Table S6. Results of ablation experiments at the encoder level and mechanism level.

	YTMR		NCP		NJP	
	RMSE	Impact	RMSE	Impact	RMSE	Impact
Full Model	0.0394	0	0.0700	0	0.0670	0
Hist Encoder	0.9118	2213.2%	1.1126	1490.2%	1.0048	1398.5%
Met Encoder	0.0603	53.0%	0.1523	117.1%	0.1724	157.3%
Geo Encoder	0.2685	581.2%	0.1835	162.3%	0.0750	11.8%
Human Encoder	0.1418	259.7%	0.1823	160.4%	0.0914	36.4%
Spatial Attention	1.0609	2591.3%	0.8367	1095.8%	1.0198	1420.9%
Site-type Awareness	2.0512	5103.7%	1.7744	2436.1%	0.9990	1390.0%
CNN Branch	0.6856	1639.4%	0.1383	97.6%	0.1326	97.7%
LSTM Branch	0.0587	48.9%	0.5026	618.4%	0.4293	540.3%

Table S7. Sensitivity coefficients of spatial attention components in the adaptive spatial attention mechanism across three regions.

	YTMR	NCP	NJP
Distance decay factor	0.311	0.077	1.107
Aquifer similarity coefficient	0.295	0.333	0.221
Site-type similarity coefficient	0.471	0.743	0.402
Watershed similarity coefficient	0.179	0.038	0.246


A1
A2
A3
A4
A5
A6
A7
A8
A9
A10
A11
A12
A13
A14
N1
N2
GWD (m)
Time
2018
2020
2022
Actual
HHA-Net
ST-GNN
GNN
Transformer
CNN-LSTM
MLP

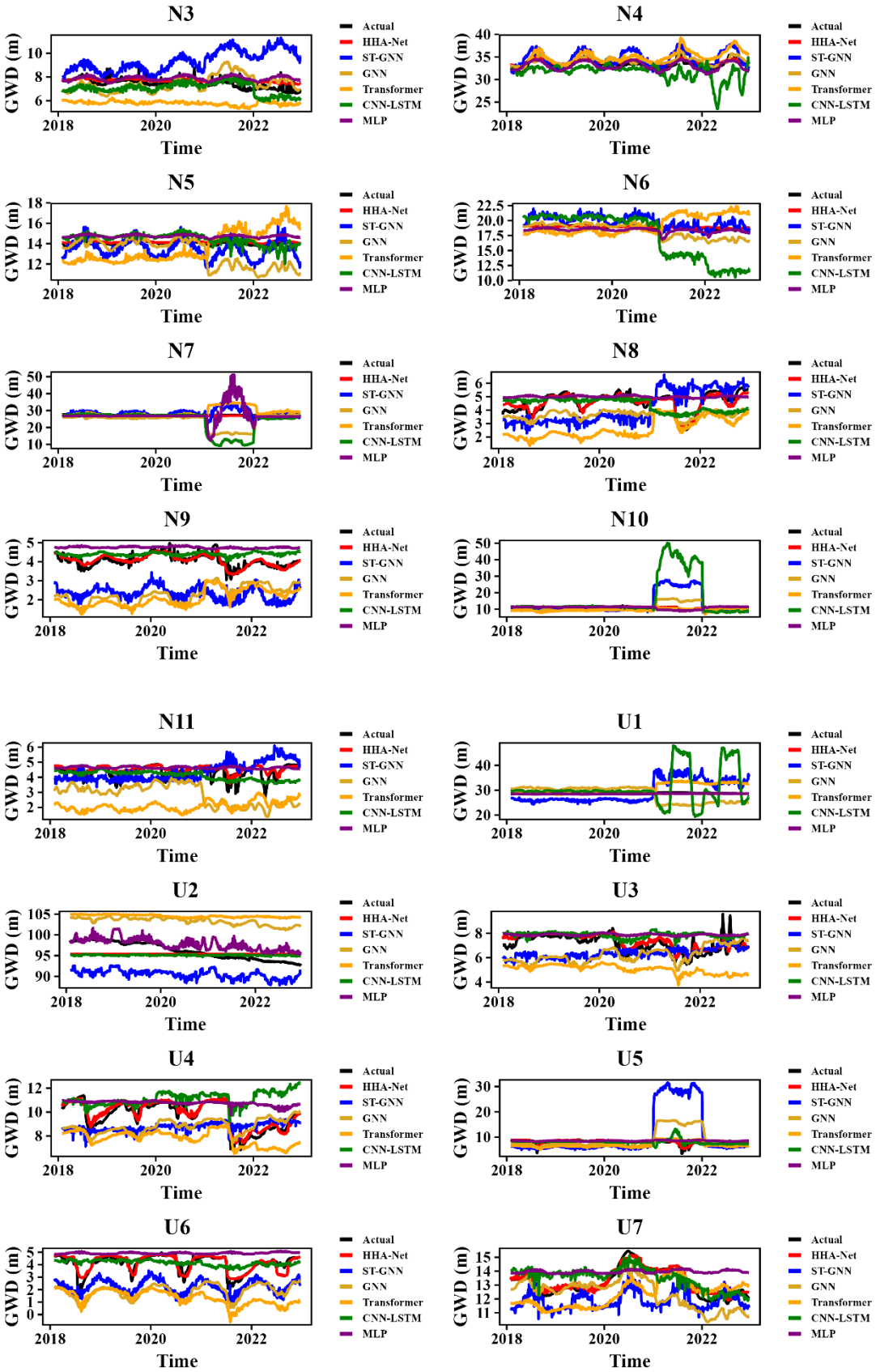
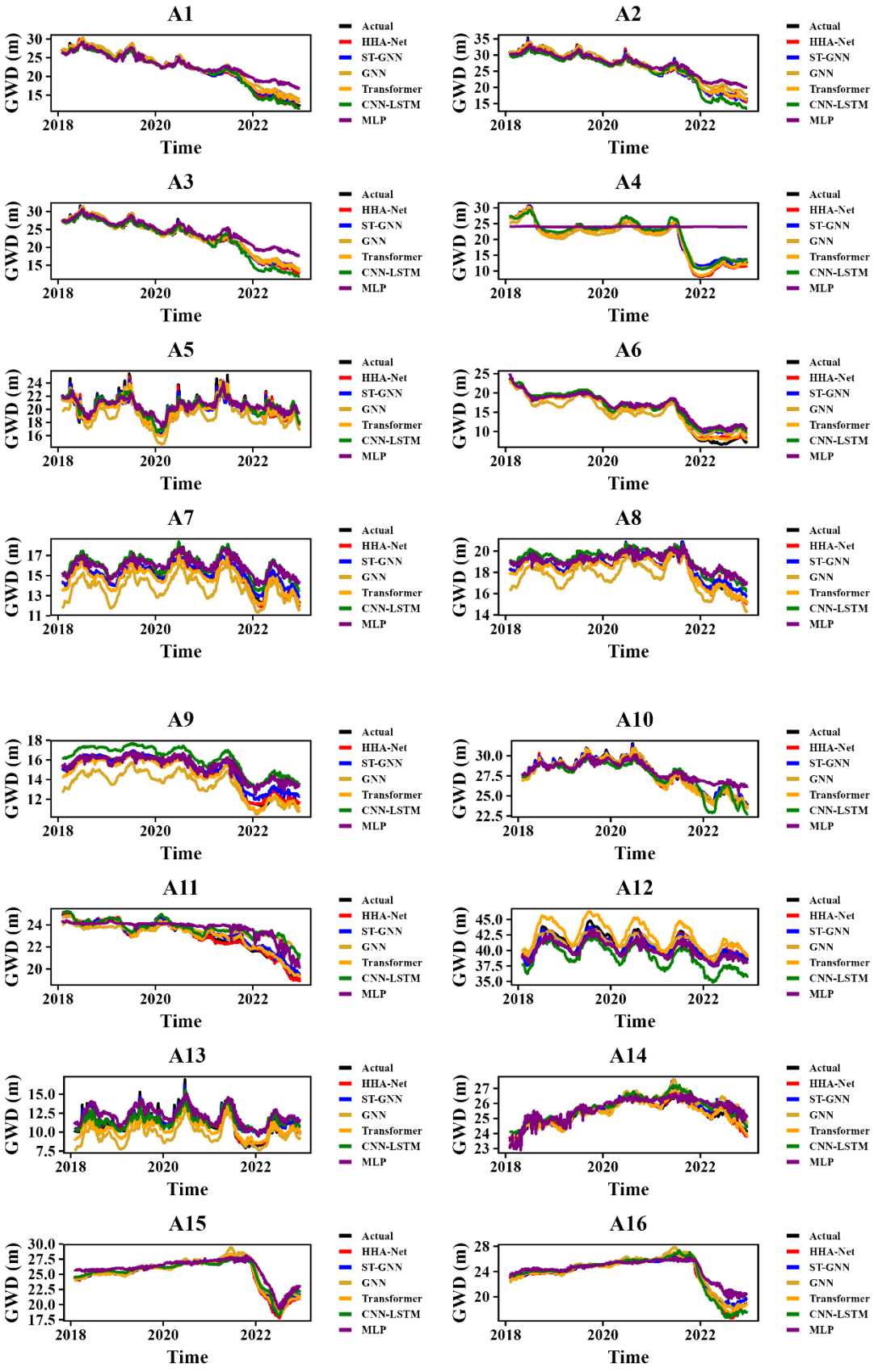


Figure S1. Comparison of 14-step GWD prediction performance across agricultural,

natural, and urban sites in YTMR.


A1
A2
A3
A4
A5
A6
A7
A8
A9
A10
A11
A12
A13
A14
A15
A16
GWD (m)
Time
2018
2020
2022
Actual
HHA-Net
ST-GNN
GNN
Transformer
CNN-LSTM
MLP

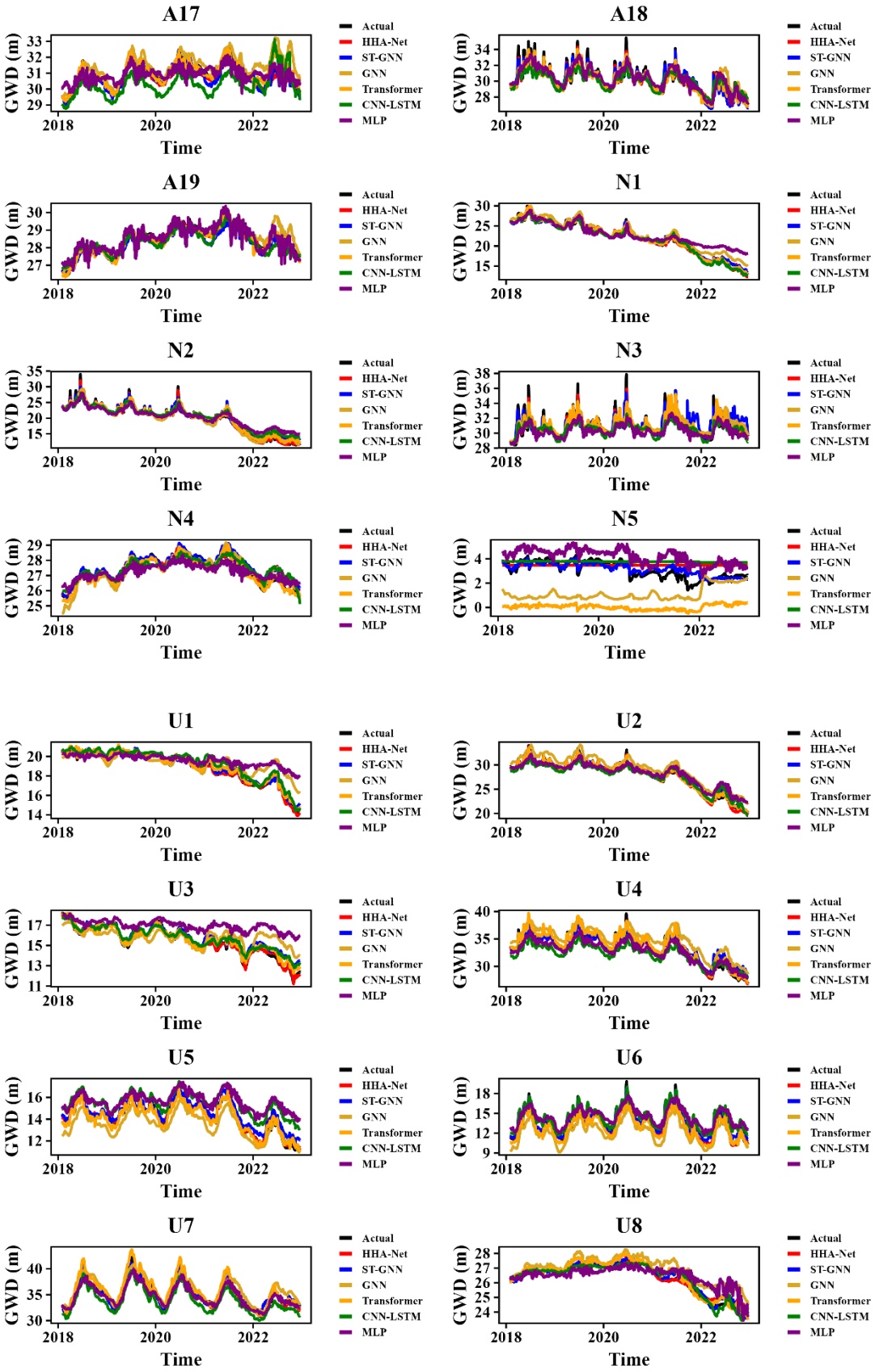
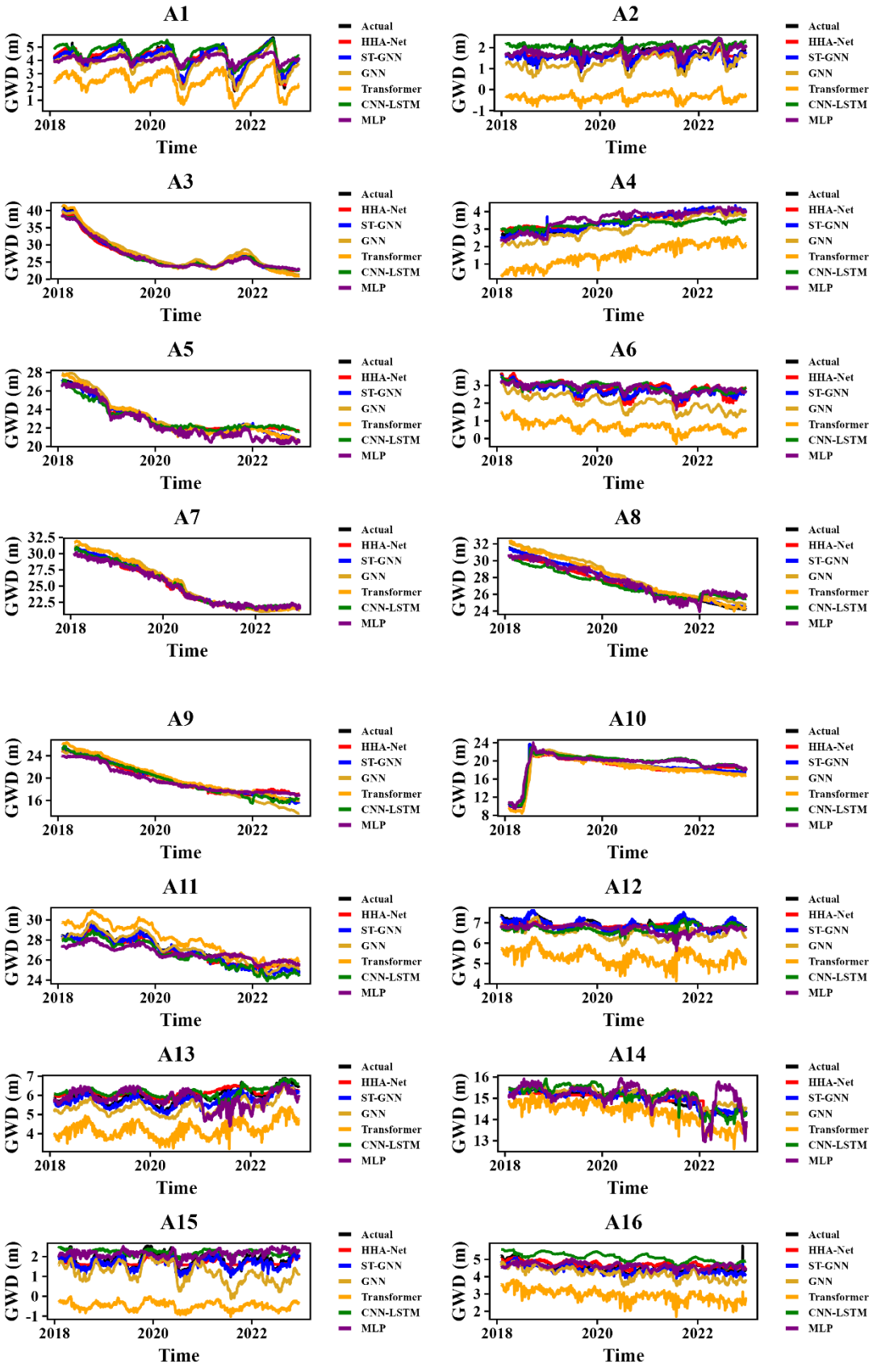
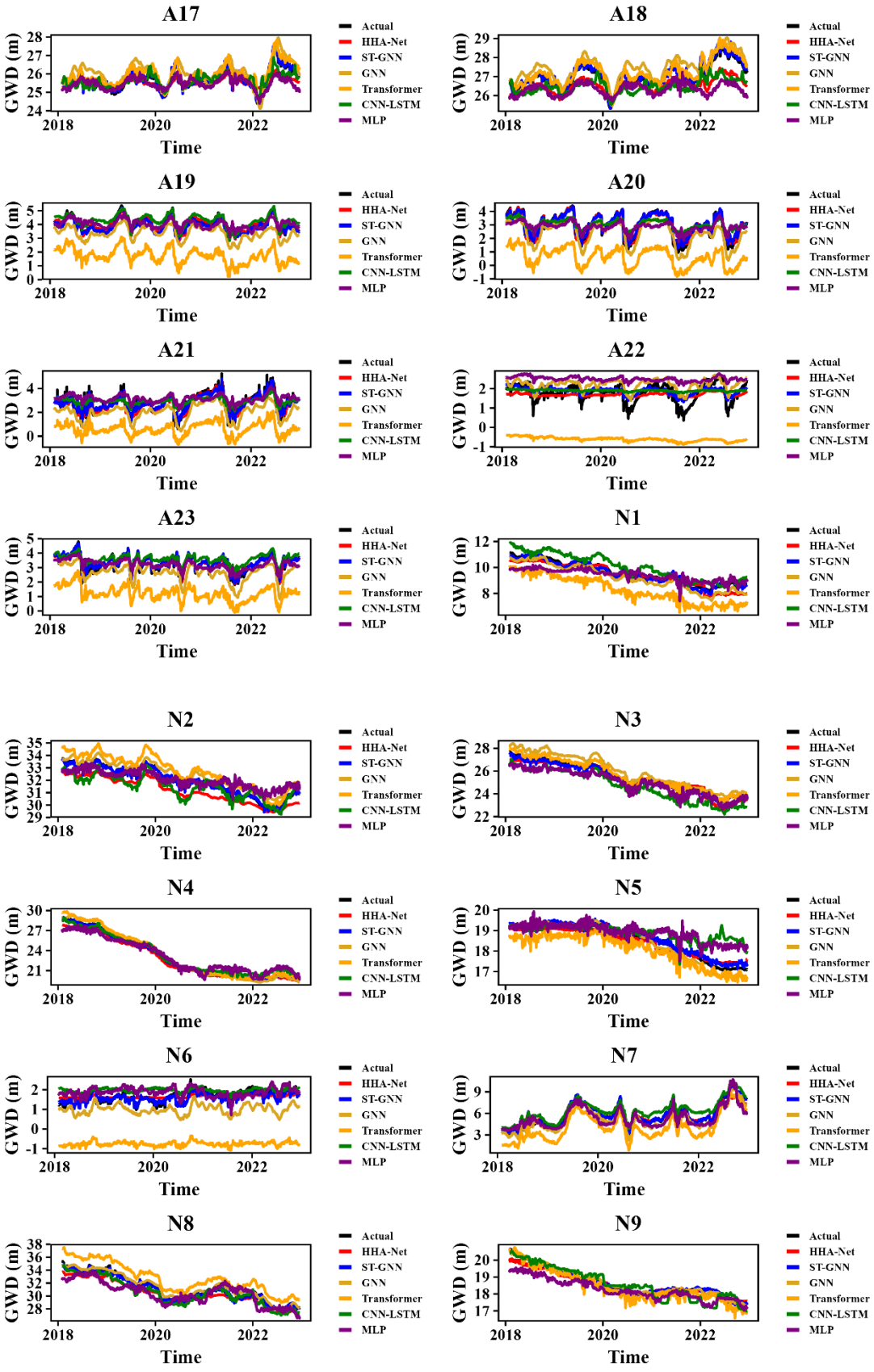
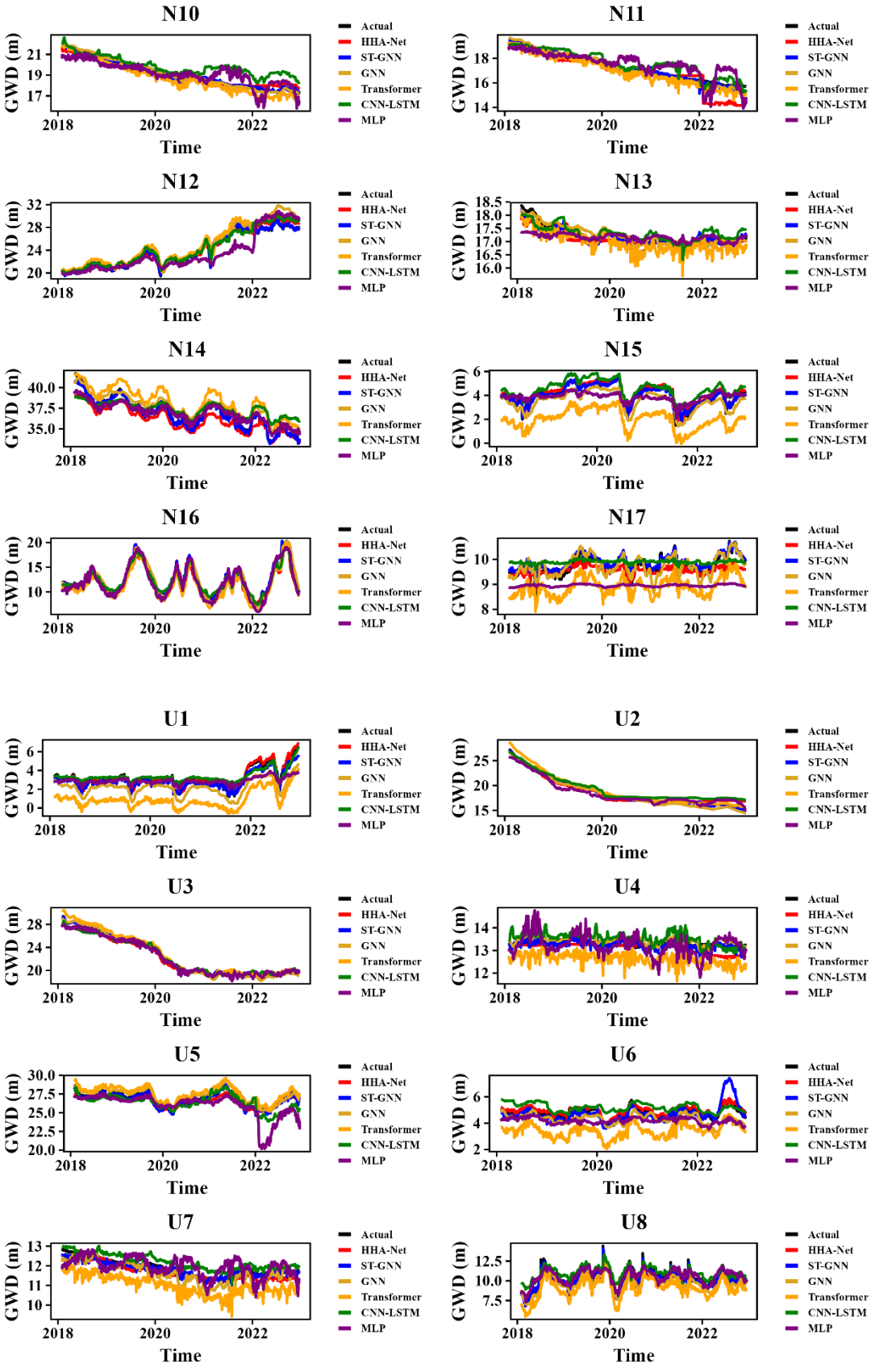


Figure S2. Comparison of 14-step GWD prediction performance across agricultural,

natural, and urban sites in NCP.


A1
A2
A3
A4
A5
A6
A7
A8
A9
A10
A11
A12
A13
A14
A15
A16
GWD (m)
Time
2018
2020
2022
Actual
HHA-Net
ST-GNN
GNN
Transformer
CNN-LSTM
MLP


A17
A18
A19
A20
A21
A22
A23
N1
N2
N3
N4
N5
N6
N7
N8
N9
GWD (m)
Time
2018
2020
2022
Actual
HHA-Net
ST-GNN
GNN
Transformer
CNN-LSTM
MLP


N10
N11
N12
N13
N14
N15
N16
N17
U1
U2
U3
U4
U5
U6
U7
U8
GWD (m)
Time
2018
2020
2022
Actual
HHA-Net
ST-GNN
GNN
Transformer
CNN-LSTM
MLP

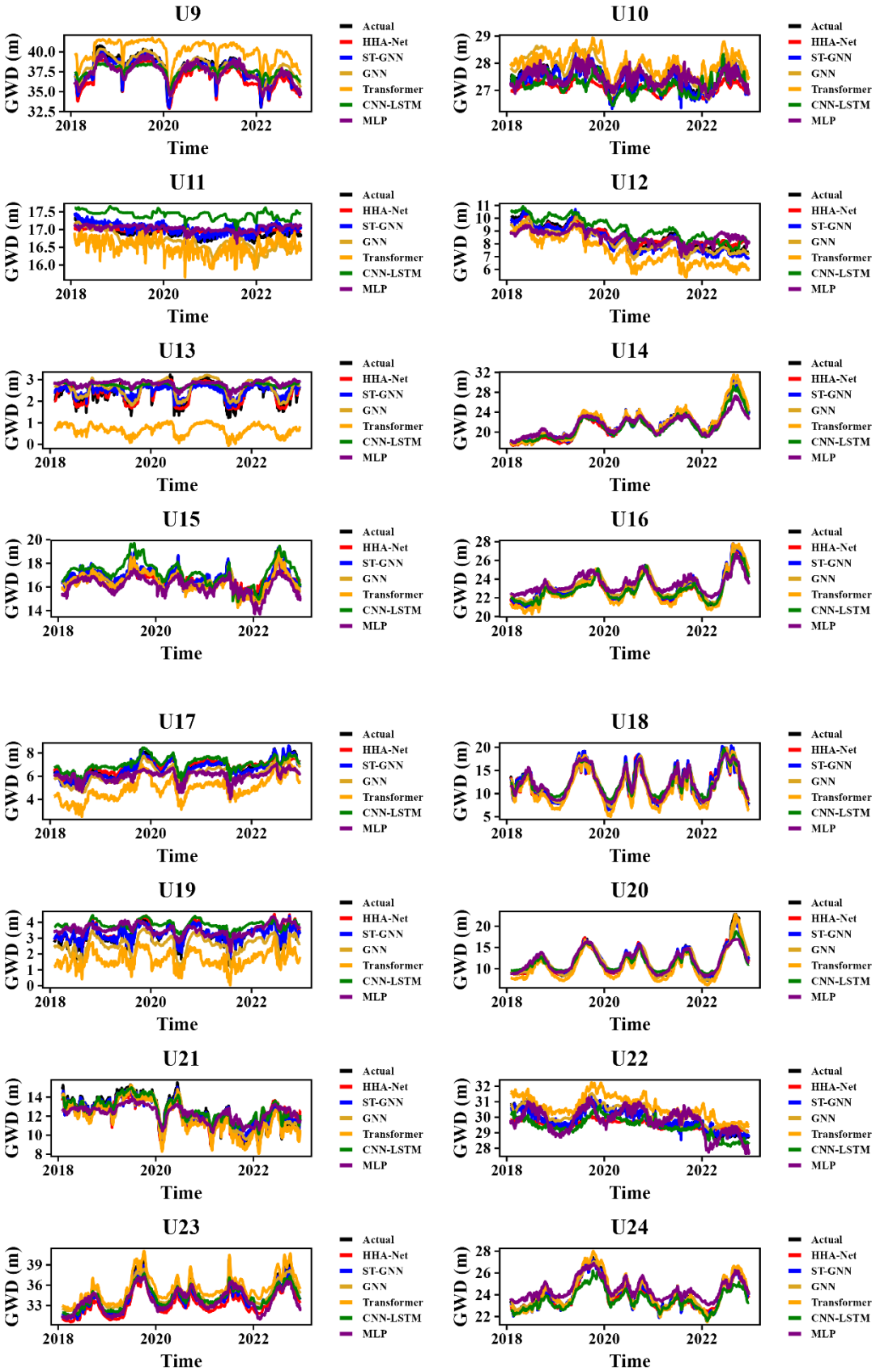
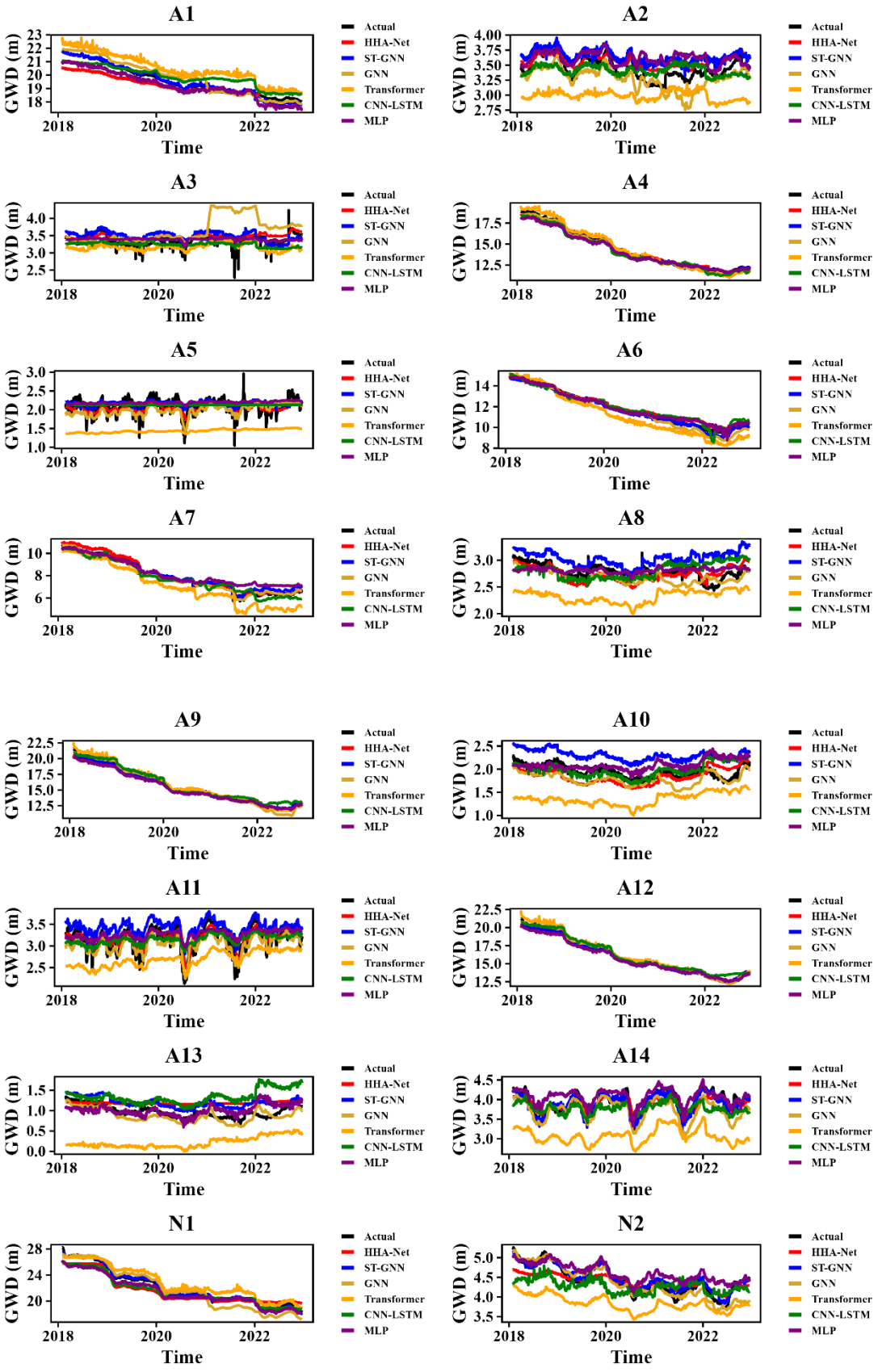
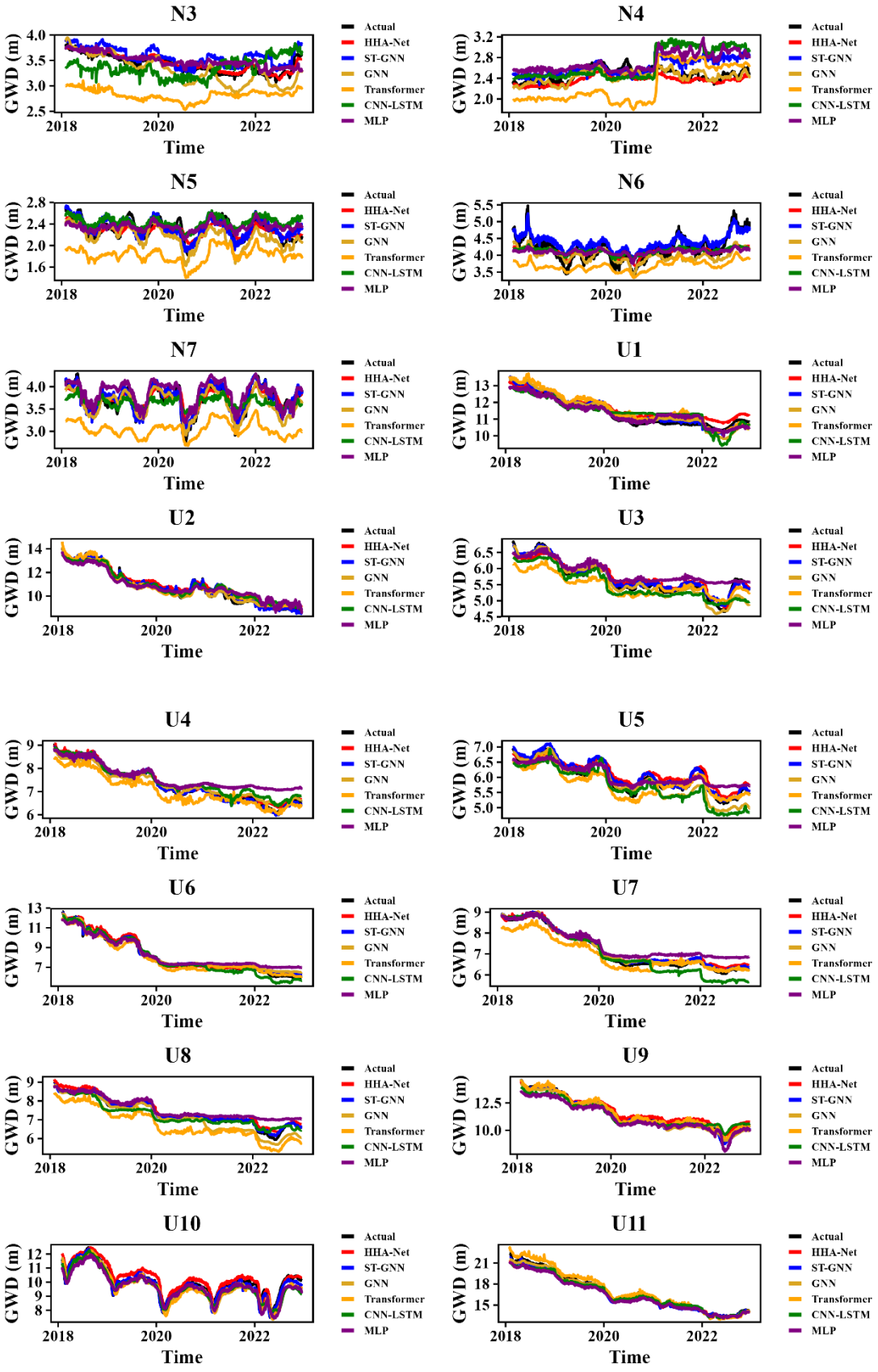


Figure S3. Comparison of 14-step GWD performance across agricultural, natural, and

urban sites in NJP.


A1
A2
A3
A4
A5
A6
A7
A8
A9
A10
A11
A12
A13
A14
N1
N2
GWD (m)
Time
2018
2020
2022
Actual
HHA-Net
ST-GNN
GNN
Transformer
CNN-LSTM
MLP


N3
N4
N5
N6
N7
U1
U2
U3
U4
U5
U6
U7
U8
U9
U10
U11
GWD (m)
Time
2018
2020
2022
Actual
HHA-Net
ST-GNN
GNN
Transformer
CNN-LSTM
MLP

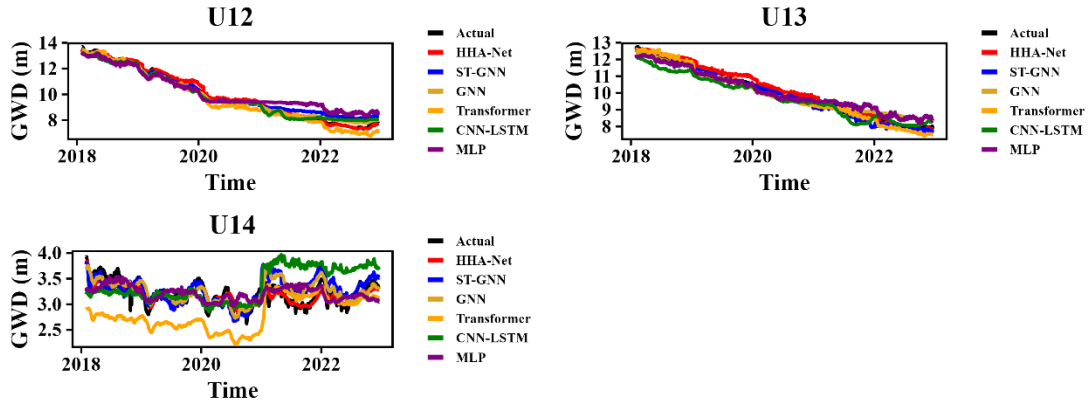


Figure S4. Comparison of 14-step GWD performance across agricultural, natural, and urban sites in LYRP.

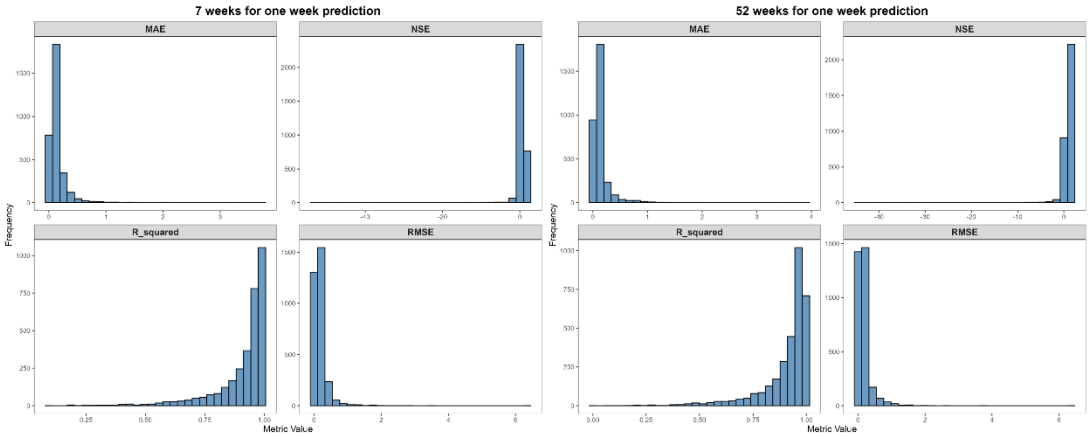


Figure S5. Distribution of prediction metrics from HHA-Net on the public GEMS-GER dataset.

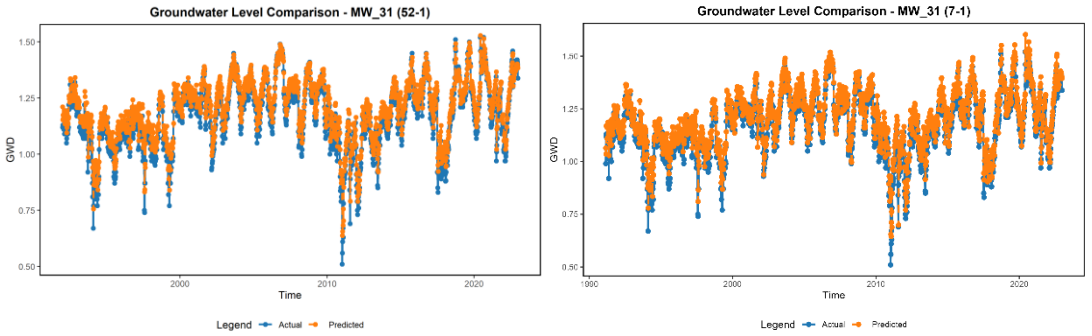


Figure S6. An example of scatter plots comparing predicted (52 weeks for 1 week prediction and 7 weeks for 1 week prediction) and observed GWD from the public GEMS-GER dataset.

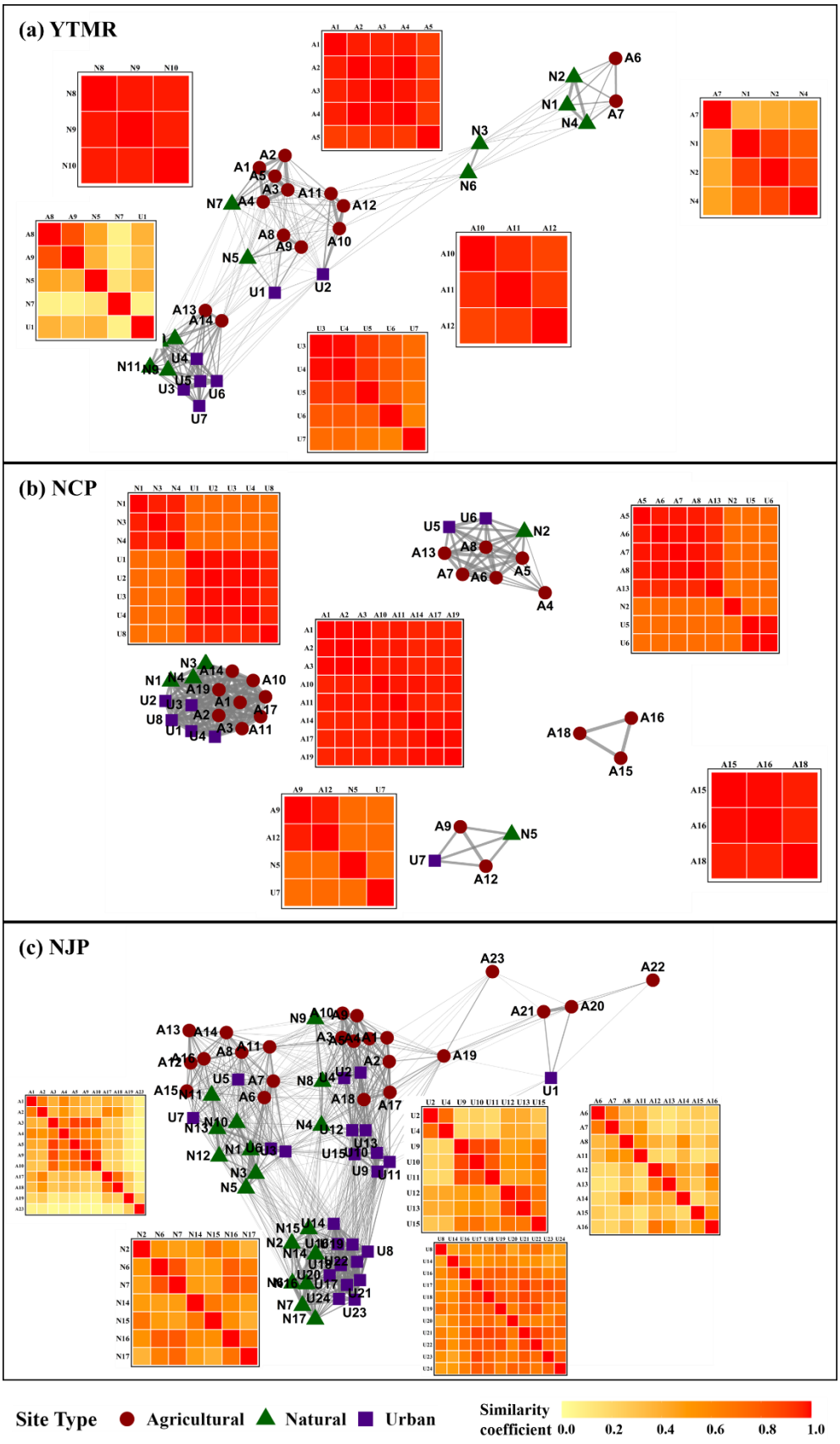


Figure S7. Spatial similarity networks for the three study regions.