CENTRAL EVERGLADES PLANNING PROJECT

System Operations towards Restoration

The *i*Model: System optimization tool

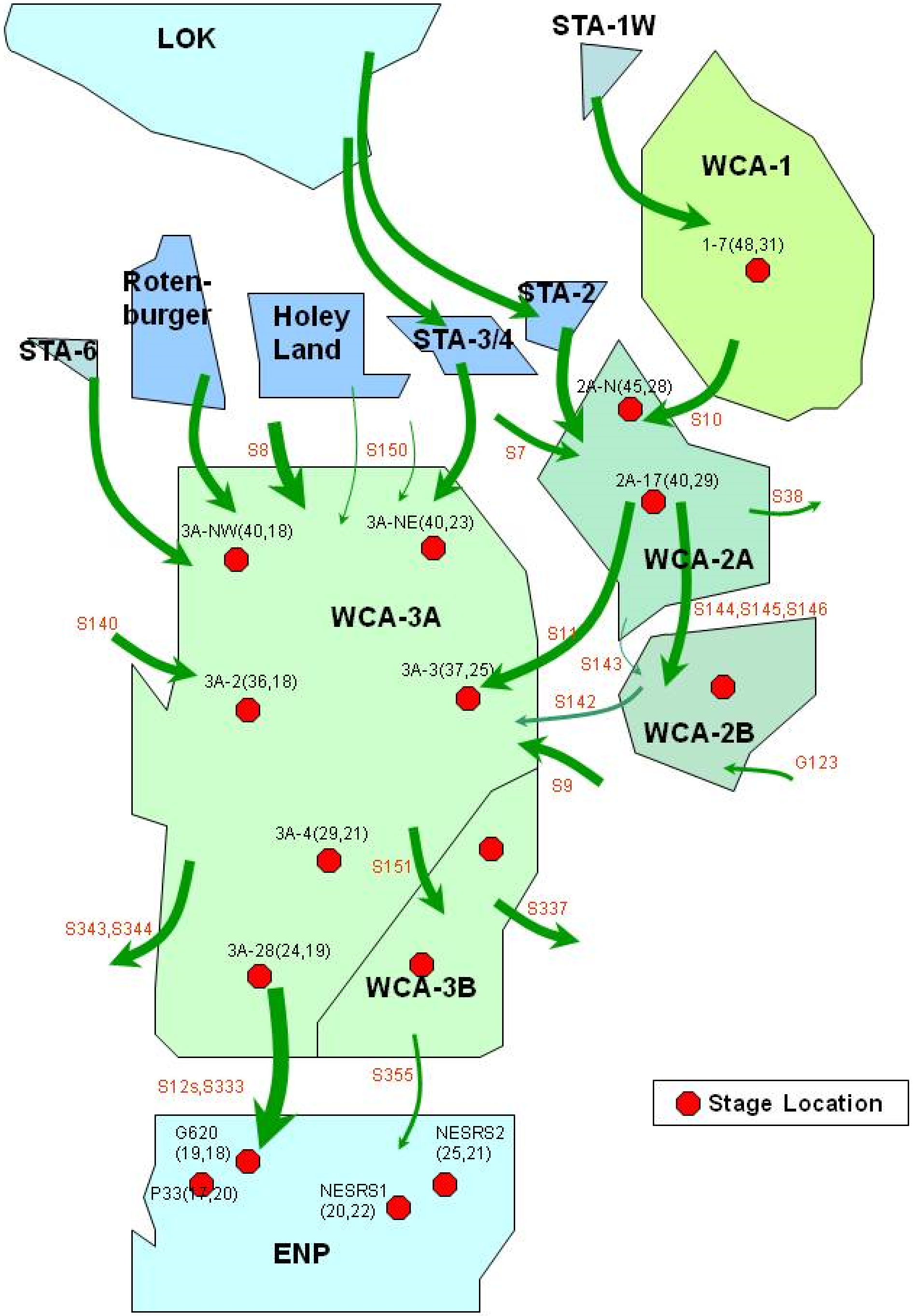
by

Alaa Ali, PhD, PE, PMP, D.WRE
Principal Engineer
Modeling-SFWMD

Presentation Outline

- Concept of Optimization?
- Approach
- Development of Hydrologic Model Emulators.
- Optimization and Genetic Algorithm
- Applications
- Summary and Conclusion

General Schematic



RESTORING THE HEART OF THE EVERGL

What is a MODEL?

•A set of mathematical equations representing the physics of water movement within the ecosystem.

•**STAGE= Ψ (rain, ET, Q_{in}, Q_{out}),**

•rain, ET, demands, and a bunch of rules → **stressors**

• STAGE → **responses**

•The solution of these equations often needs advanced numerical methods and computer programming.

• SFWMM and RSM are examples of hydrologic models

What is utility of hydrologic MODELS?

- Simulate system response to system's stressors under certain conditions (alternative).
- Test response sensitivities due to variation of system stressors, landscape, components, rules, or different climatic scenarios (alternatives).

Can these models answer this question?

- How to Operate the system (i.e., estimate inflow, outflow, and intra-flow deliveries at all key structures) to achieve desired spatiotemporal hydro-patterns (stage) and still meet all other system's imposed demands and capacities.

Can these models answer this question?

- Flow deliveries (**stressors**)
- Desired hydro-patterns (**responses**)
- System’s demands and capacities

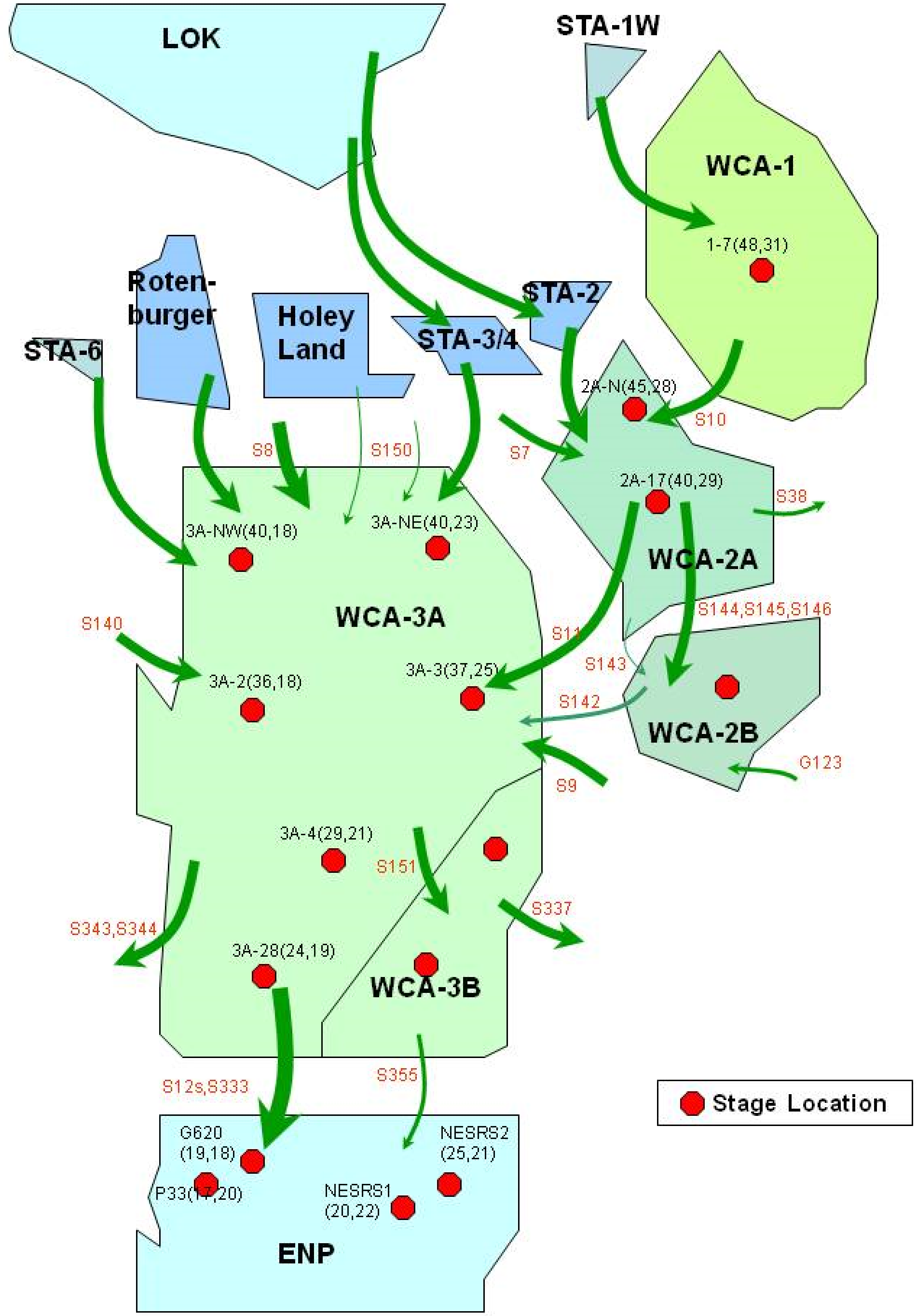
Can these models answer this question?

- Not suited for this kind of problems where the stages are input and the flow deliveries are output.
- These models can be used, however, in a trial and error framework. To capture the spatiotemporal variability of prescribed stages, 100's of model runs are needed.
- Given 1 ½ day run time of one model run, This brute force approach is practically infeasible.
- Output processing is a difficult task and the realization of an optimal solution is subjective and will be subject to controversy.

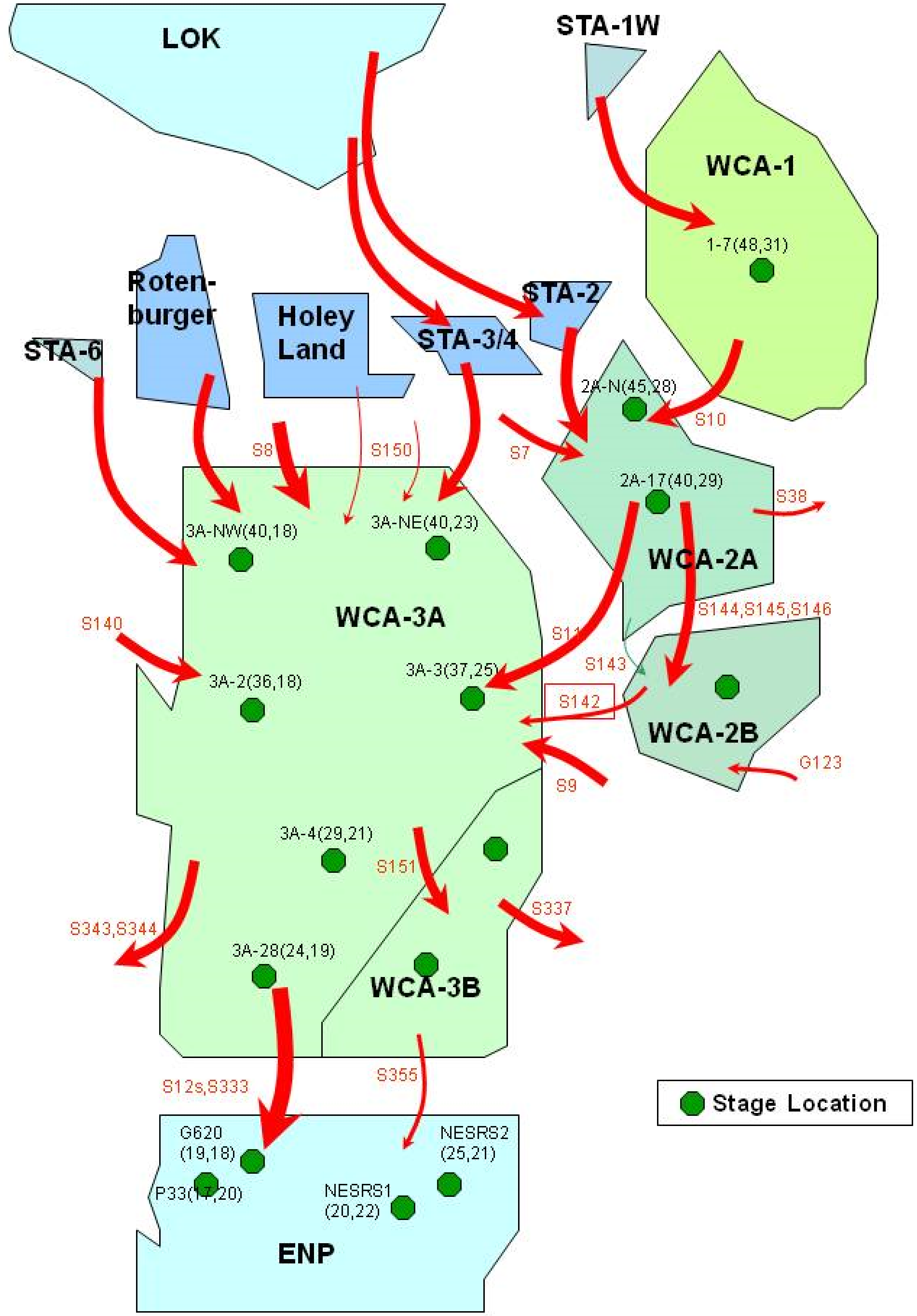
How to make an output an input and one of the inputs an output?

- Models typically model stage (output) as a function of rain, pet, inflows, and outflows (inputs)
- **Direct Model:** → $y = f(x)$
  - stage = Ψ (rain, ET, Q_{in}, Q_{out}),
- Direct model can not control flow deliveries to achieve certain concurrent stage values.
- **Naïve Inverse Model** → $x = g(y)$
  - $Q_{in/out} = \Phi$(rain, ET, stage)
- **True Inverse Model** → $x = f^{-1}(y)$
  - Find: $Q_{in/out} = \Omega$(rain, ET, Ψ^{-1} {stage})

DIRECT MODEL, → RSM



iNVERSE MODEL, → iModel



SAME THING DIFFERENT NAMES?

	DIRECT MODELS	INVERSE MODELS
FLOW DELIVERIES	STRESSORS	DECISION VARIABLES
HYDRO-PATTERNS (STAGE)	RESPONSES	TARGETS
SYSTEM FEATURES	•DEMANDS •STRUCTURES •RULES	CONSTRAINTS

Inverse Modeling Approach

- Develop super fast "**direct**" model(s) (Ψ) to be managed by an appropriate optimization algorithm
- The optimization has an Objective (e.g., achieve certain targets) and a set of Constraints (e.g., Flood control, water supply, components' capacities).

Procedure

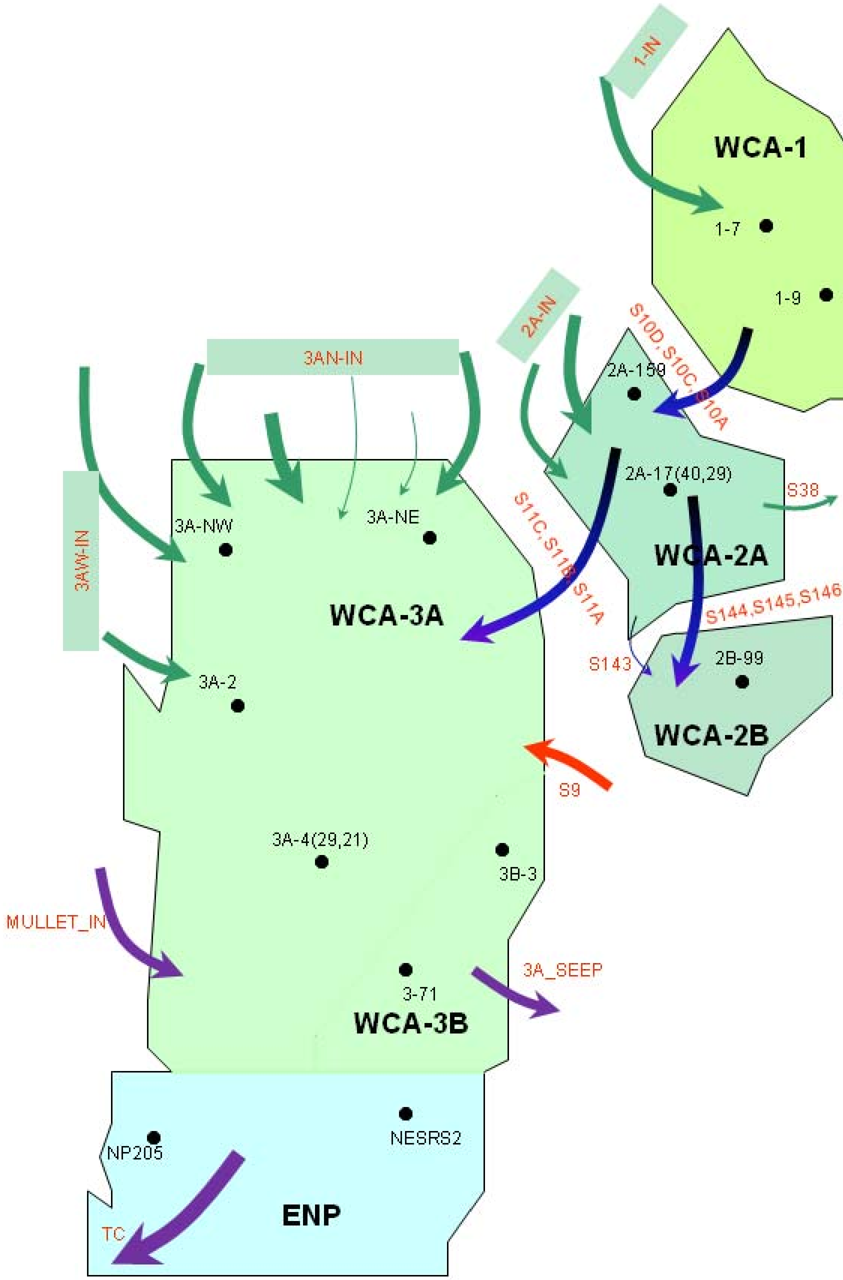
- In the absence of historical data taken from a representative system, such a system needs to be modeled (e.g., by RSM)
- From a completed simulation, for each separate water bodies (WCAs, ENP, STAs, …etc.), extract time series data at all flow structures, headwater, tailwater, and target locations.
- For each water body , identify all water supply, flood control, and any other applicable constraints
- For each water body, develop a Hydrologic Model Emulator, HME, using the techniques developed by Ali, 2009, to predict stage and transect flows at the identified target locations as function of inflows and outflows and net rainfall.

Procedure

- Employ an optimization scheme to manage and optimize concurrent performance of the different water body's HMEs to approach the desired targets subject to linear and nonlinear constraints and weights.

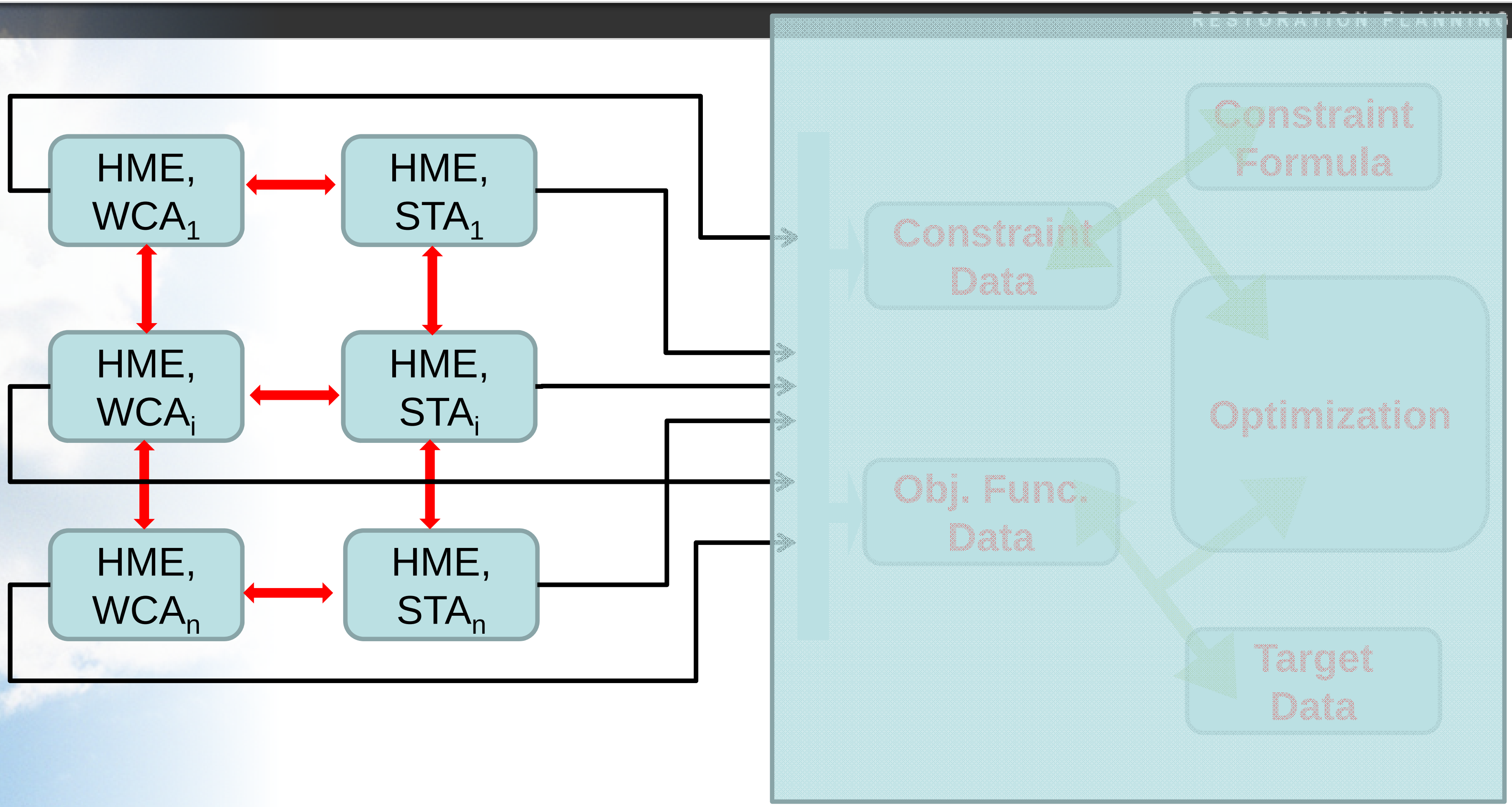
Procedure

- Objective Function
  - Minimize an error score of the actual solution Ψ from the desired target.
- Constraints
  - Environmental: (e.g., minimum flow delivery)
  - Water Supply (e.g., certain demand thresholds)
  - Flood Control (e.g., capacities, maximum stages)
  - Hydrologic/Hydraulic (e.g., conveyance capacity)



GLADES OVERALL SYSTEM DECOMP.

iModel Schematic



HME Representation

- HMEs of the iModel are represented by Multivariate State Space Model implemented as Autoregressive Artificial Neural Network model with exogenous input.
- Ali 2009 and previous presentations provide a full monograph about this model development.

Sample HME

- Decompartmentalized WCA3s+ENP:
  - **You express the change in stage** at the trigger locations, and structure headwater or tailwater locations **as function of** inflows, outflows, rainfall, and PET)

$$\Delta Stage_{(t-1,t)}\begin{pmatrix}3A\_NW, 3A\_NE, 3A\_2, 3A\_4, 3B\_3, \_3B\_71, NESRS2, \\ NP205, S11sTw, mullet\_IN, -3AB\_SEEP, -ENP\_SEEP, -T\_C\end{pmatrix}$$
$$= \Psi\left(3AN\_IN, 3AW\_IN, S11s, S9, Rain_{net}\right)$$

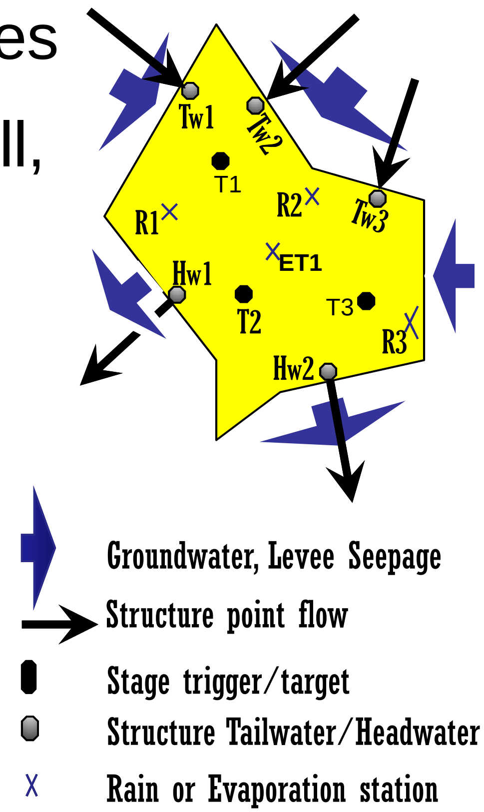
  - **Add the change in stage to the stage at time step t-1**

$$Stage_{(t)} = Stage_{(t-1)} + \Delta Stage_{(t-1,t)}$$

ARX formulation

$$s_t = \sum_{i=0}^{q-1} \Gamma_i u_{t-i} + \sum_{j=1}^{p} \Phi_j s_{t-j} + \nu + \omega_t$$

- *q,p* → input and output maximum time delays (model orders),
- *n*, *m* → number of state and exogenous variables
- ***u*** → *mxq* residual exogenous input (flow, rainfall, and ETp) matrix,
- **s** → *p x n* residual state variable (stage) matrix
- Γ → *nxm* exogenous coefficient matrix
- Φ → *p x p* state transition matrix
- ν → bias vector
- ω → random vector with zero mean and a covariance Matrix.



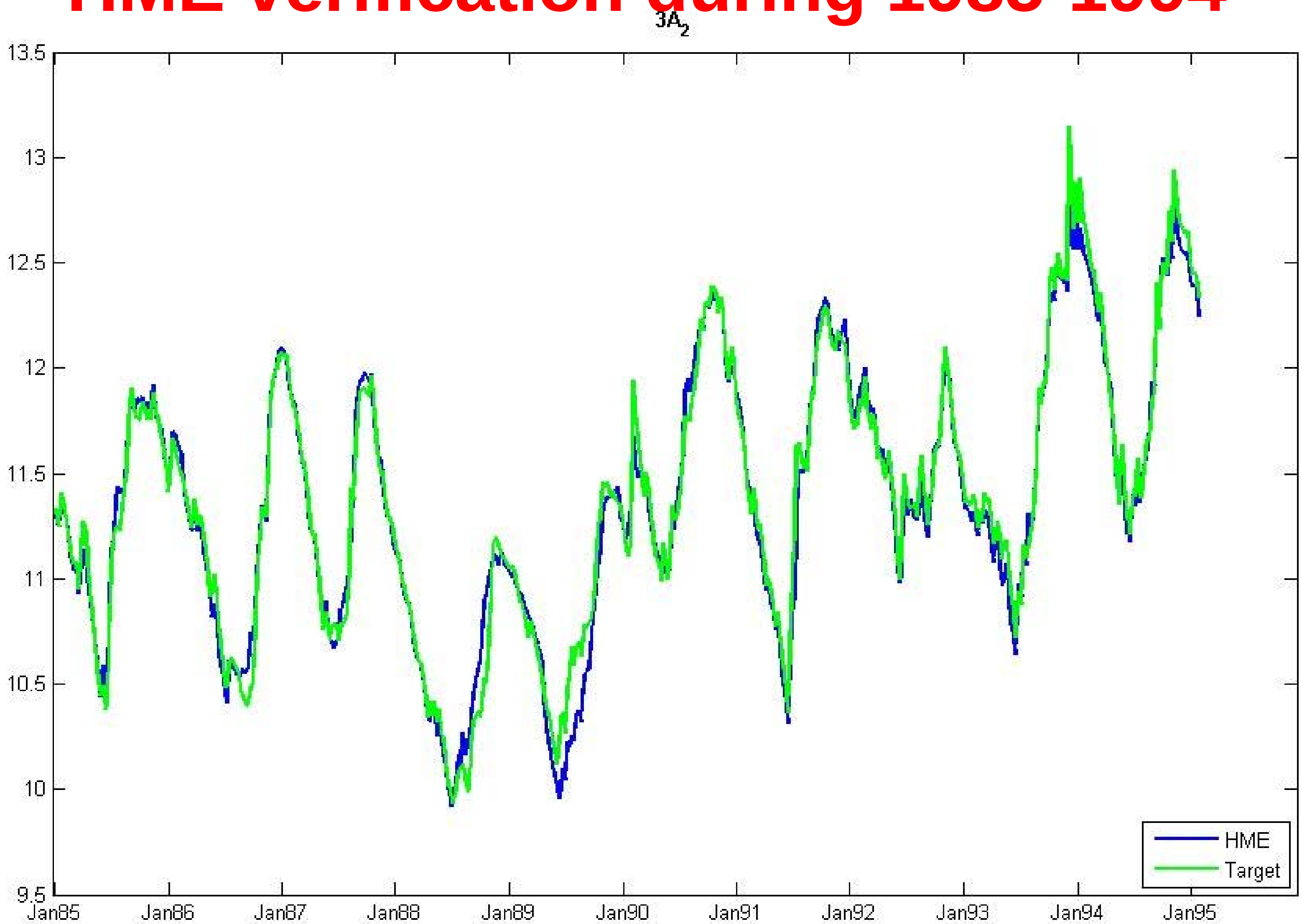
HME implementation by ANN

- HMEs of the iModel are represented by Multivariate State Space Model implemented as Autoregressive Artificial Neural Network model with exogenous input.
- Ali 2009

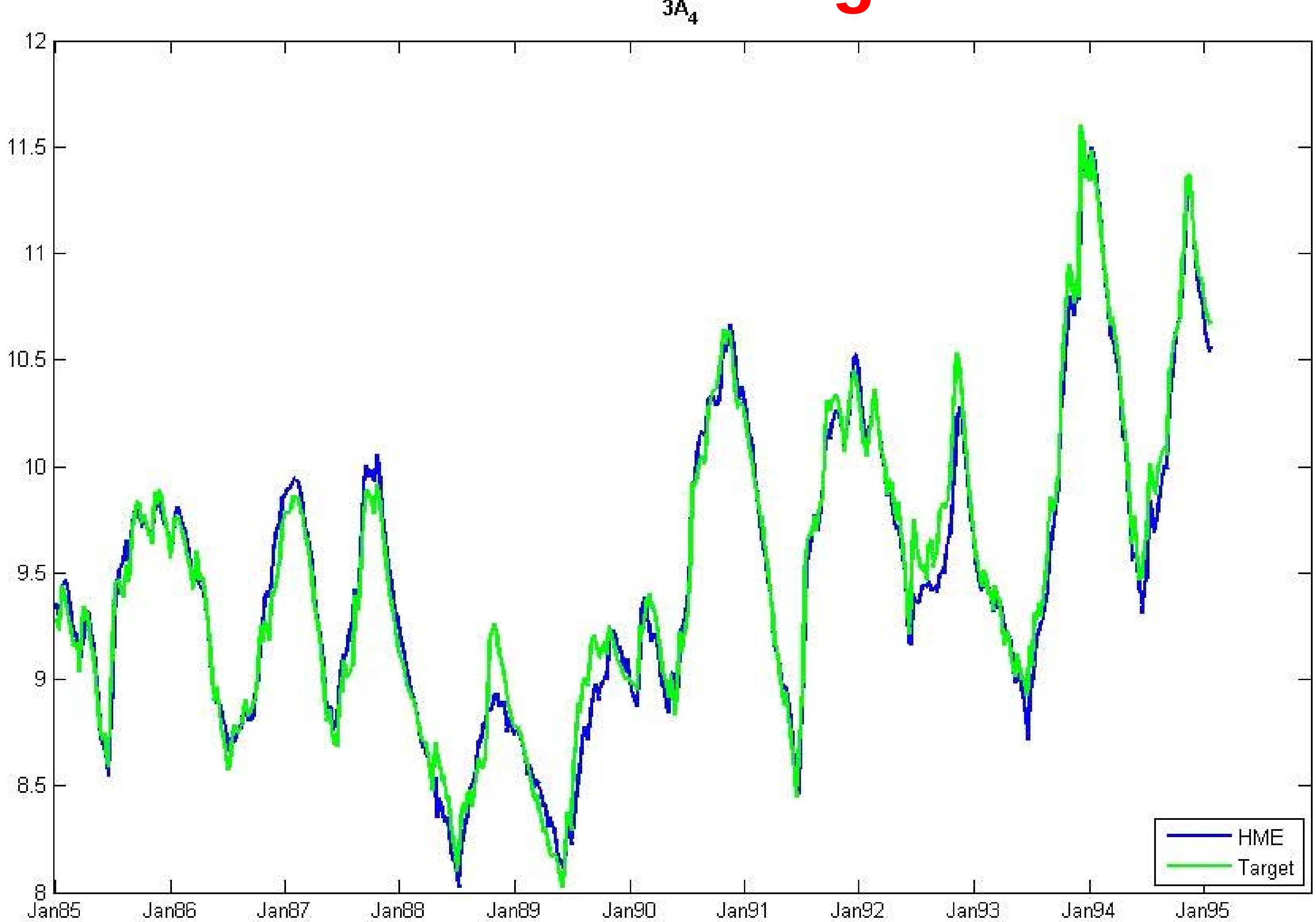
HME results

- Time Step: Weekly

HME verification during 1985-1994



HME verification during 1985-1994



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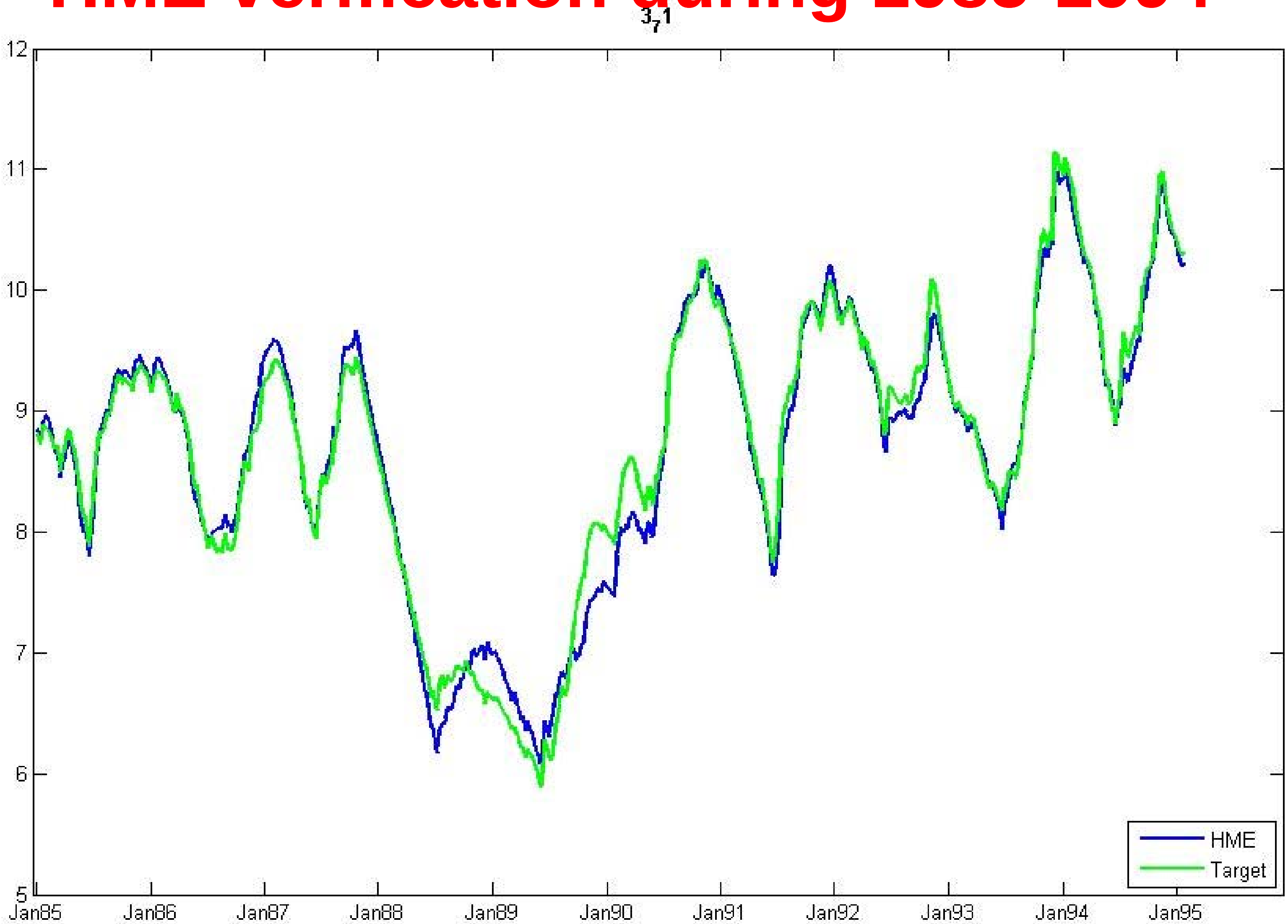

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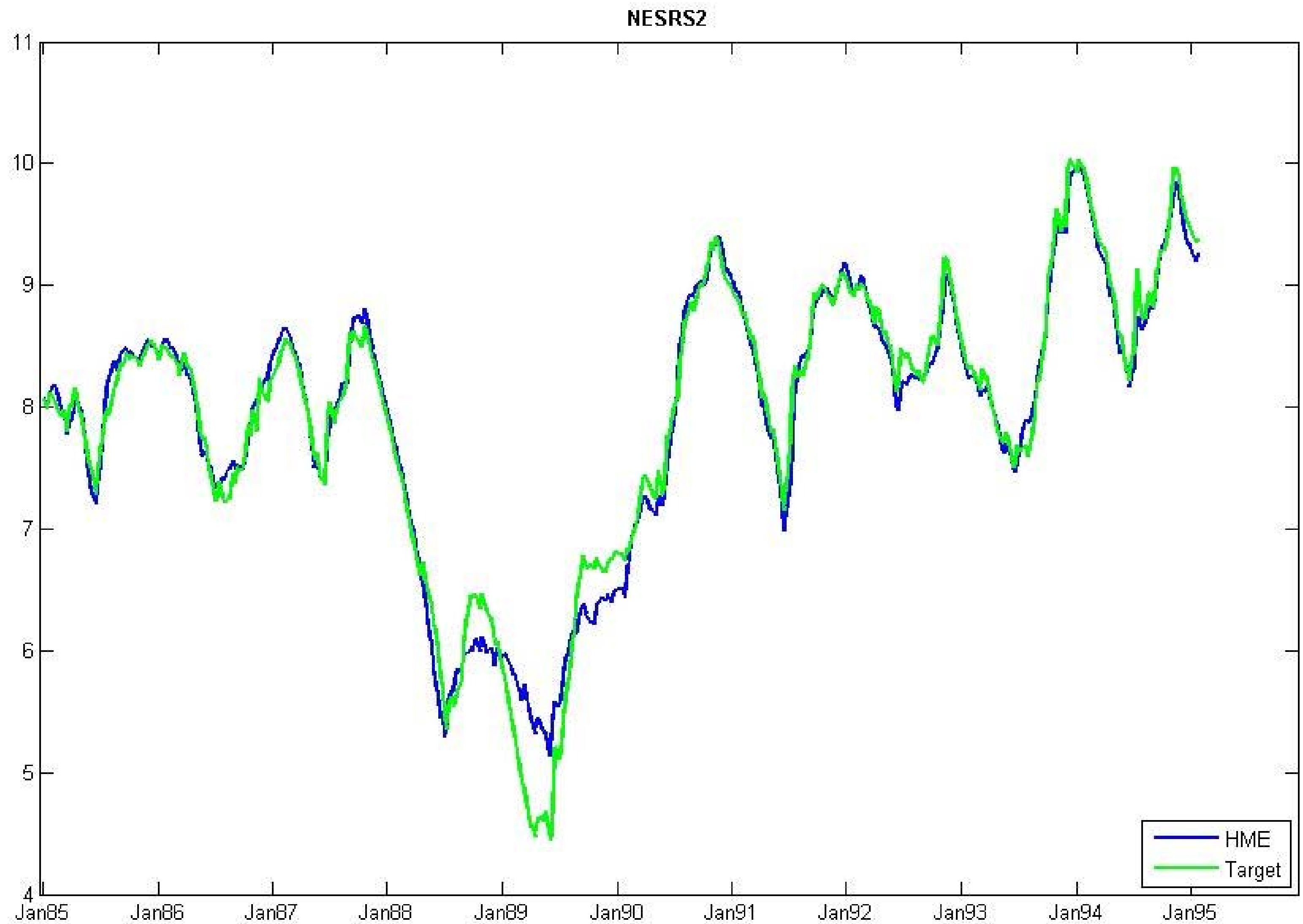
HME verification during 1985-1994



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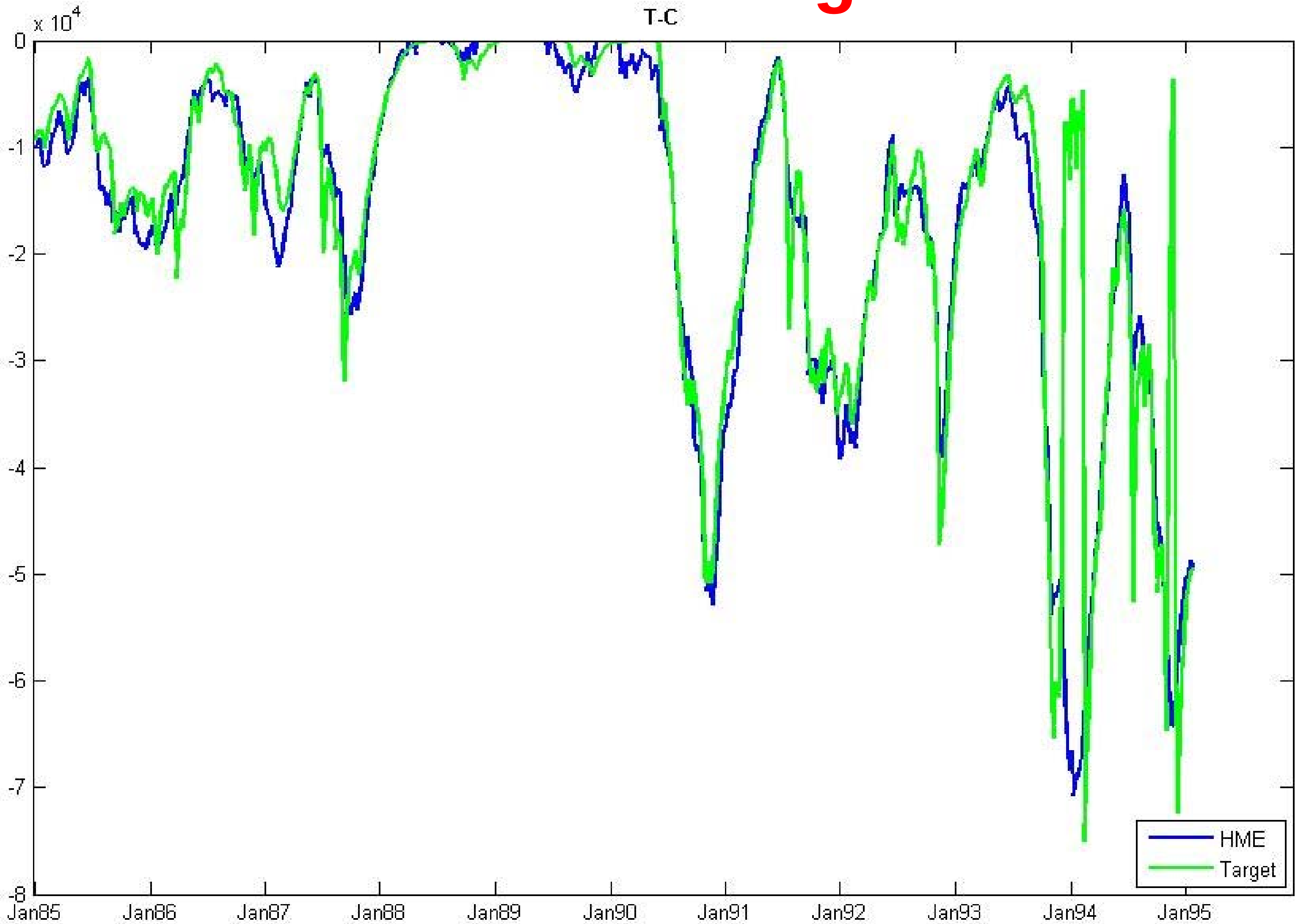

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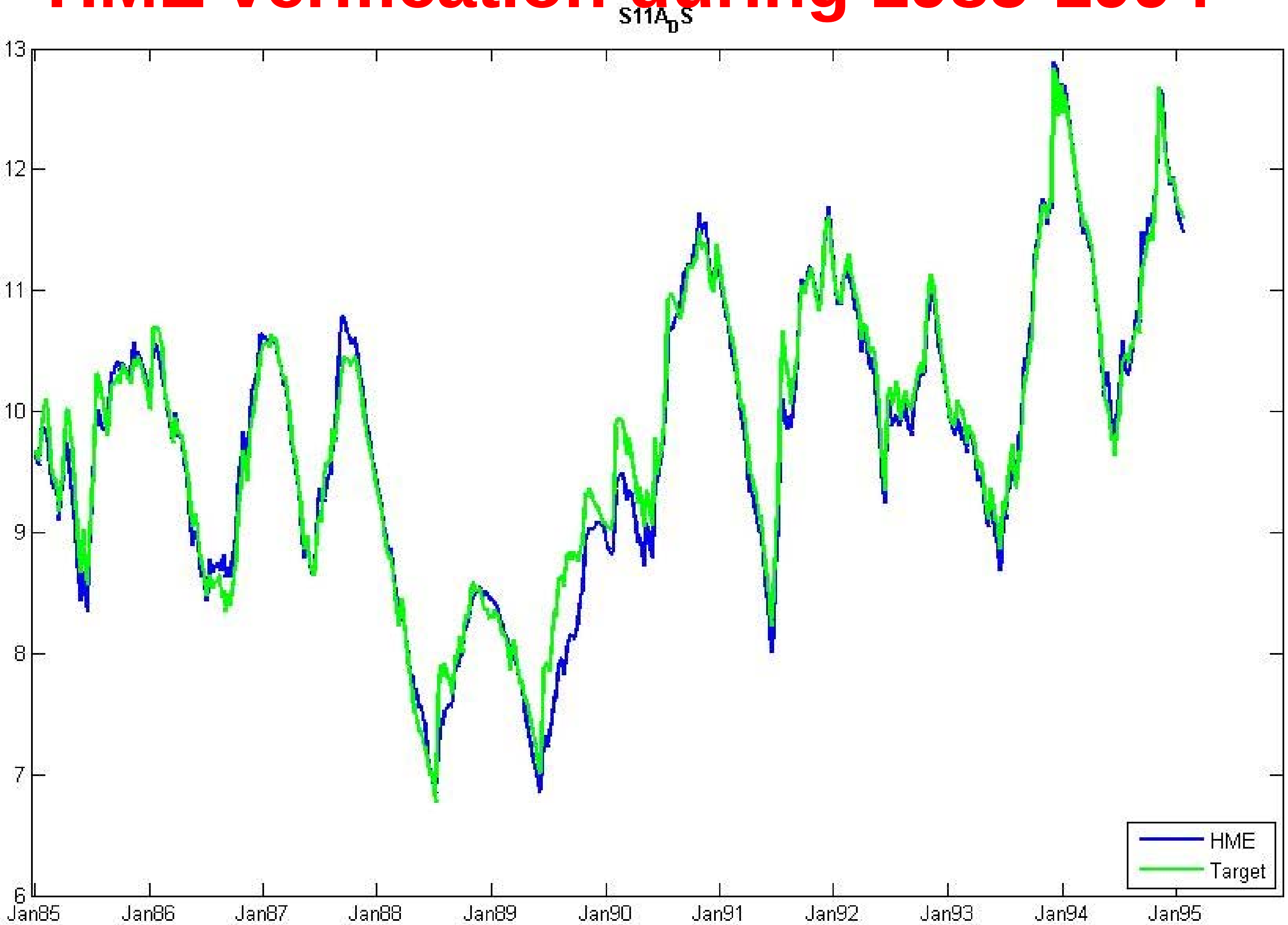

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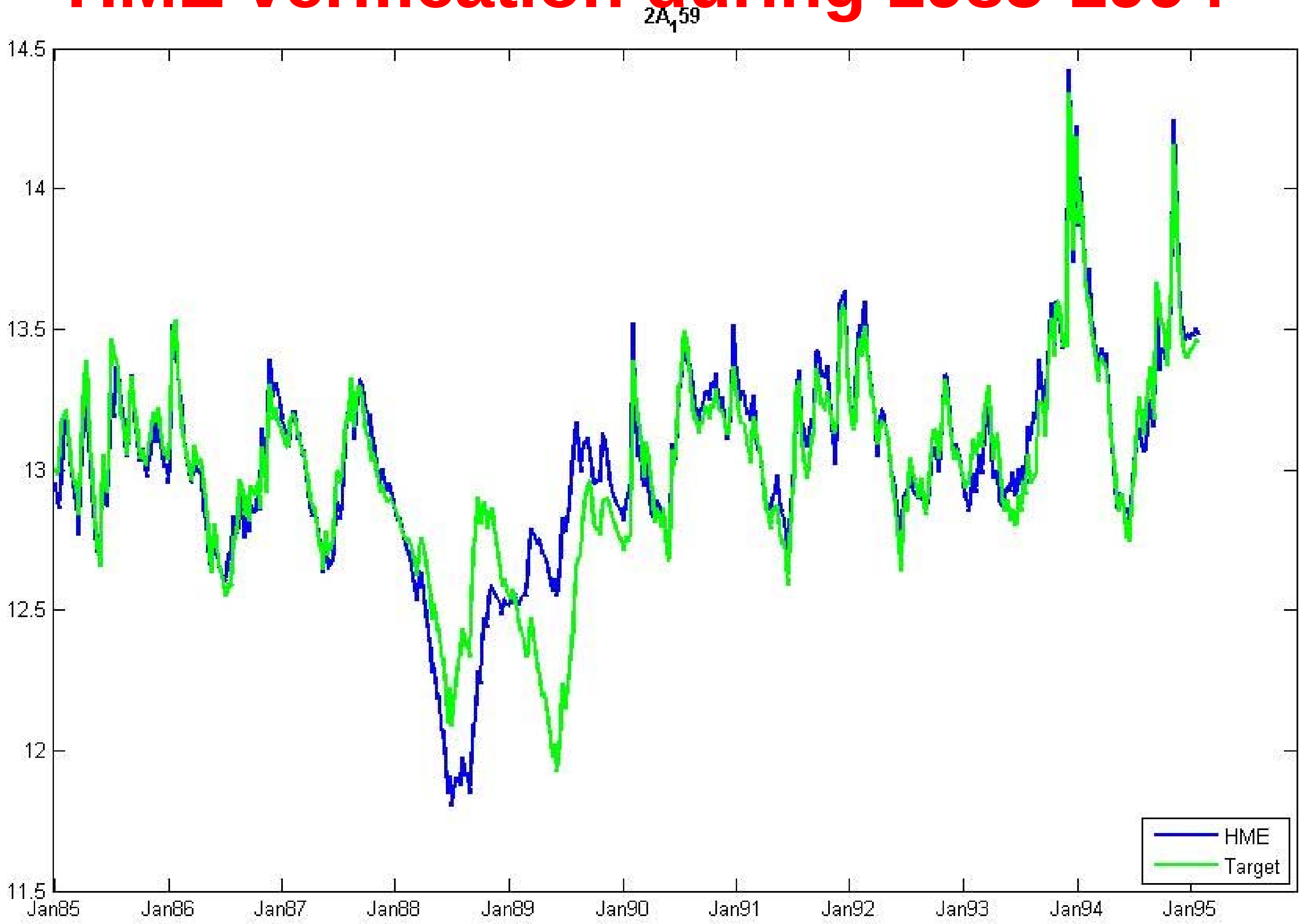

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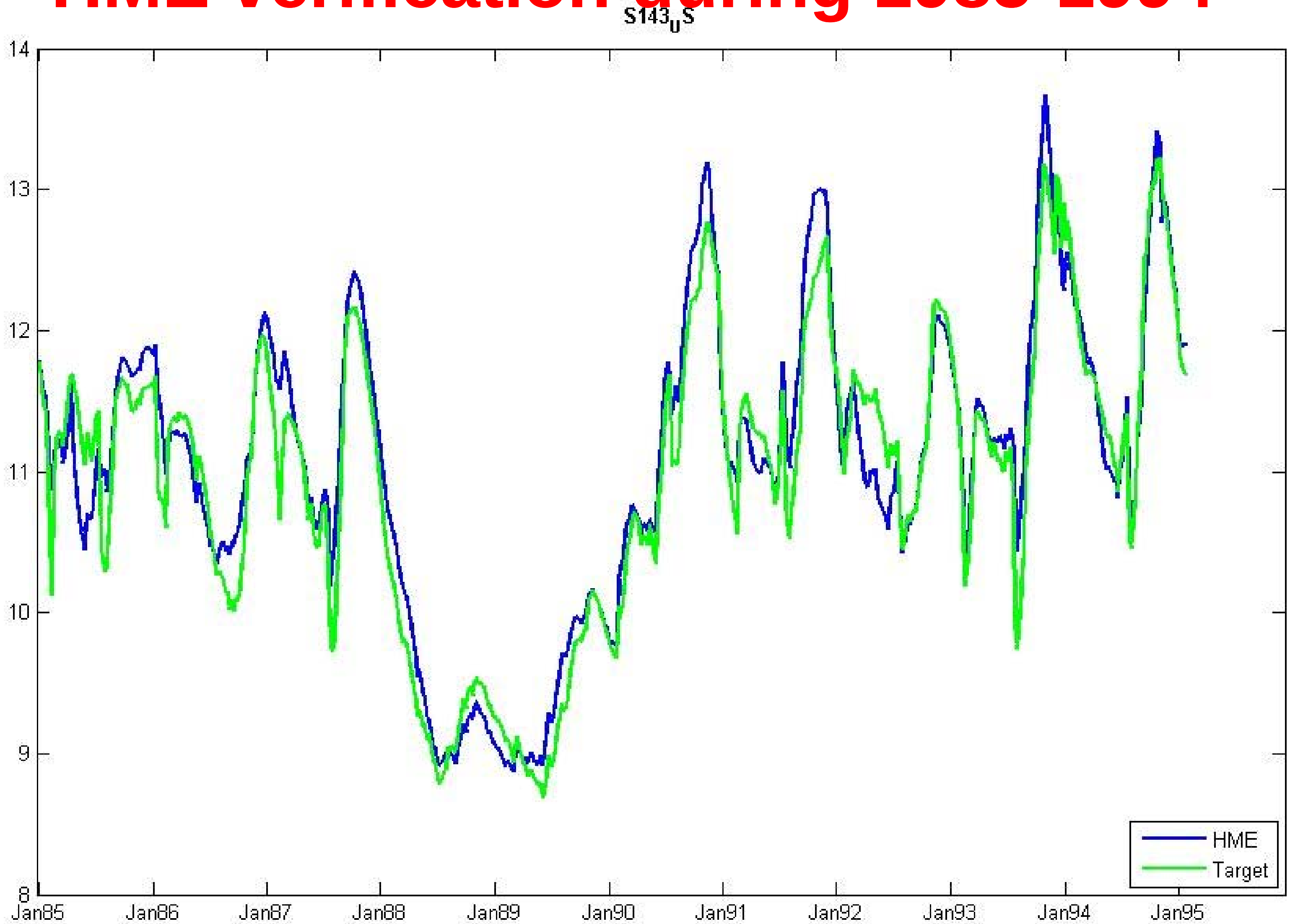

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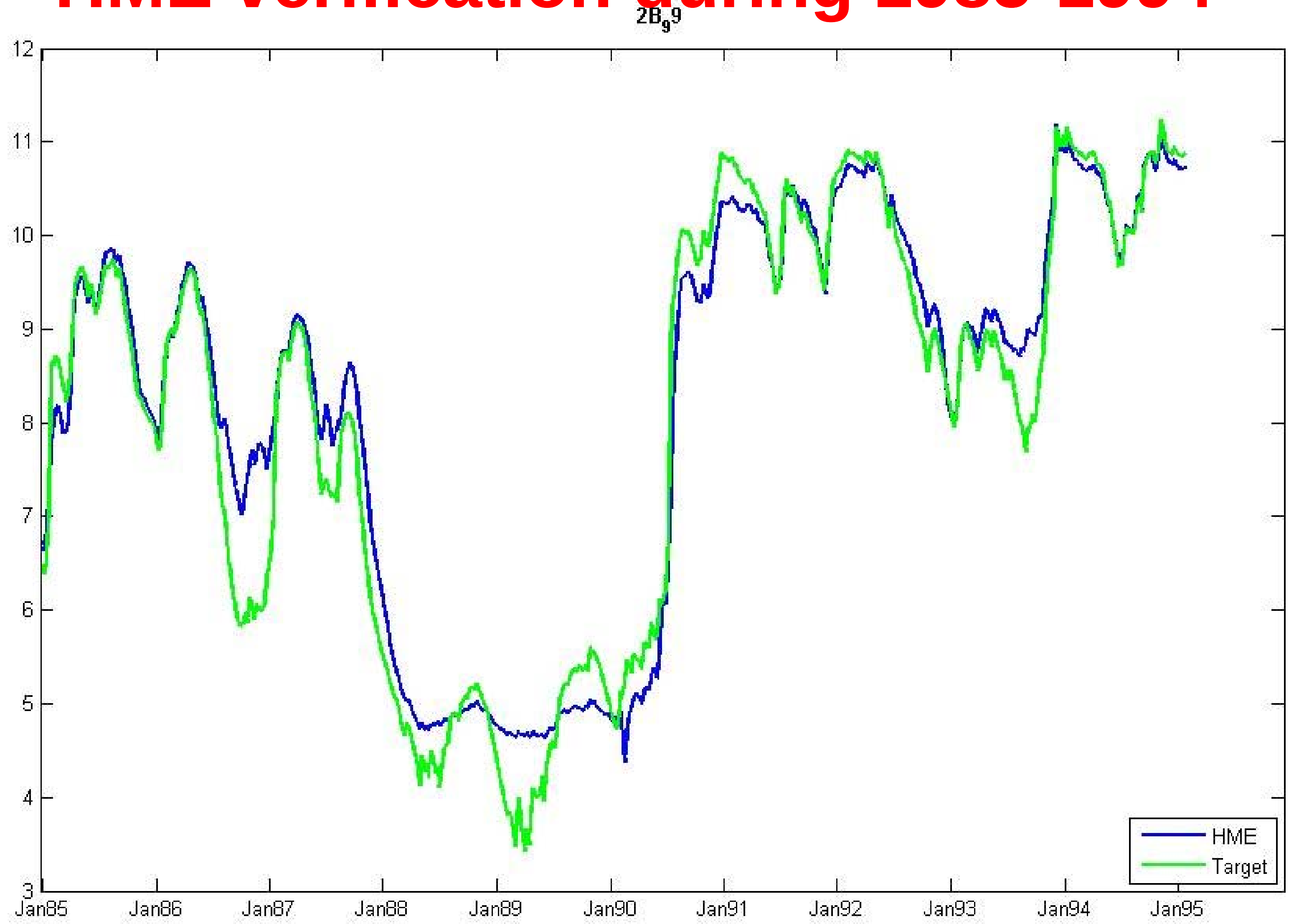

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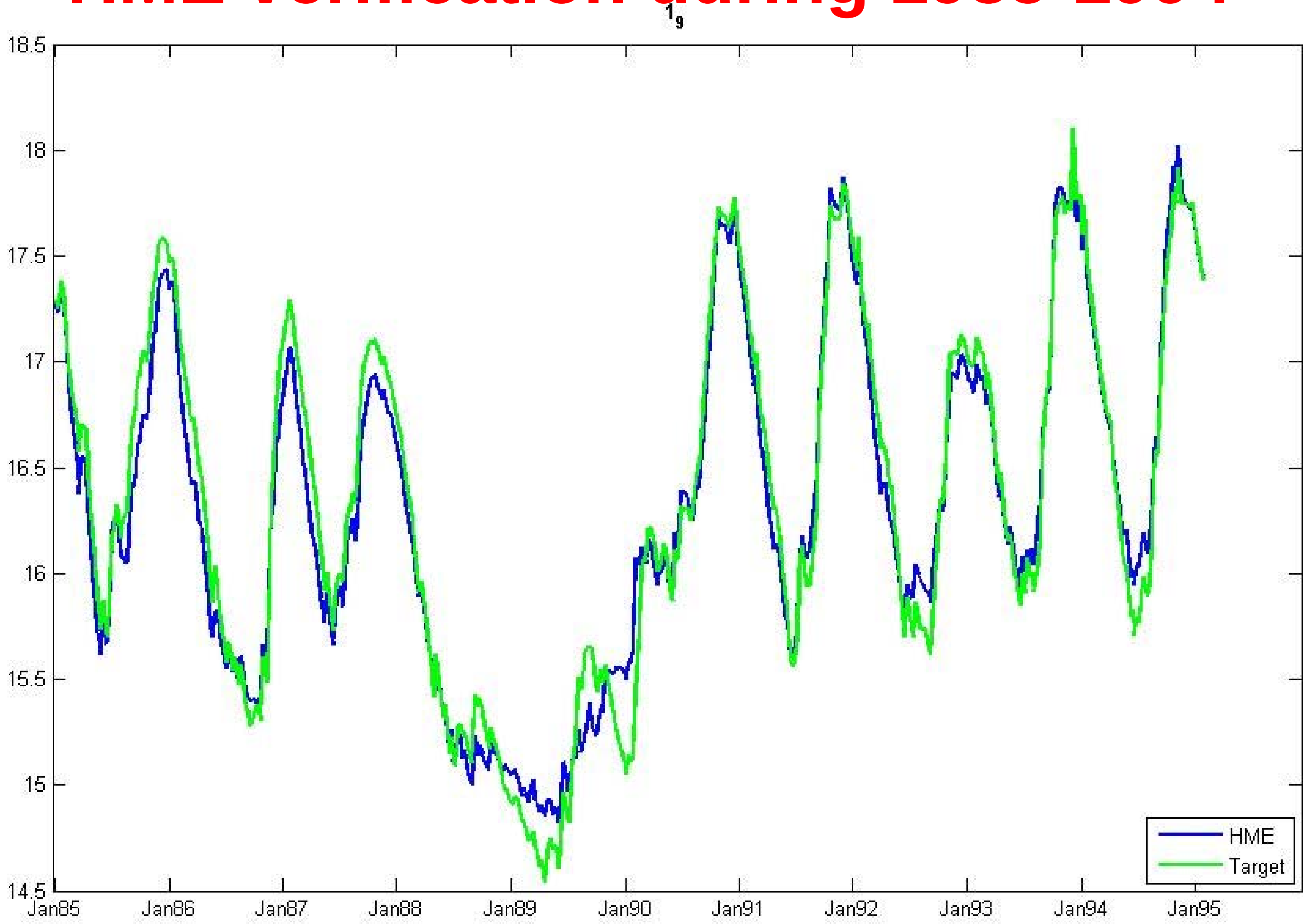
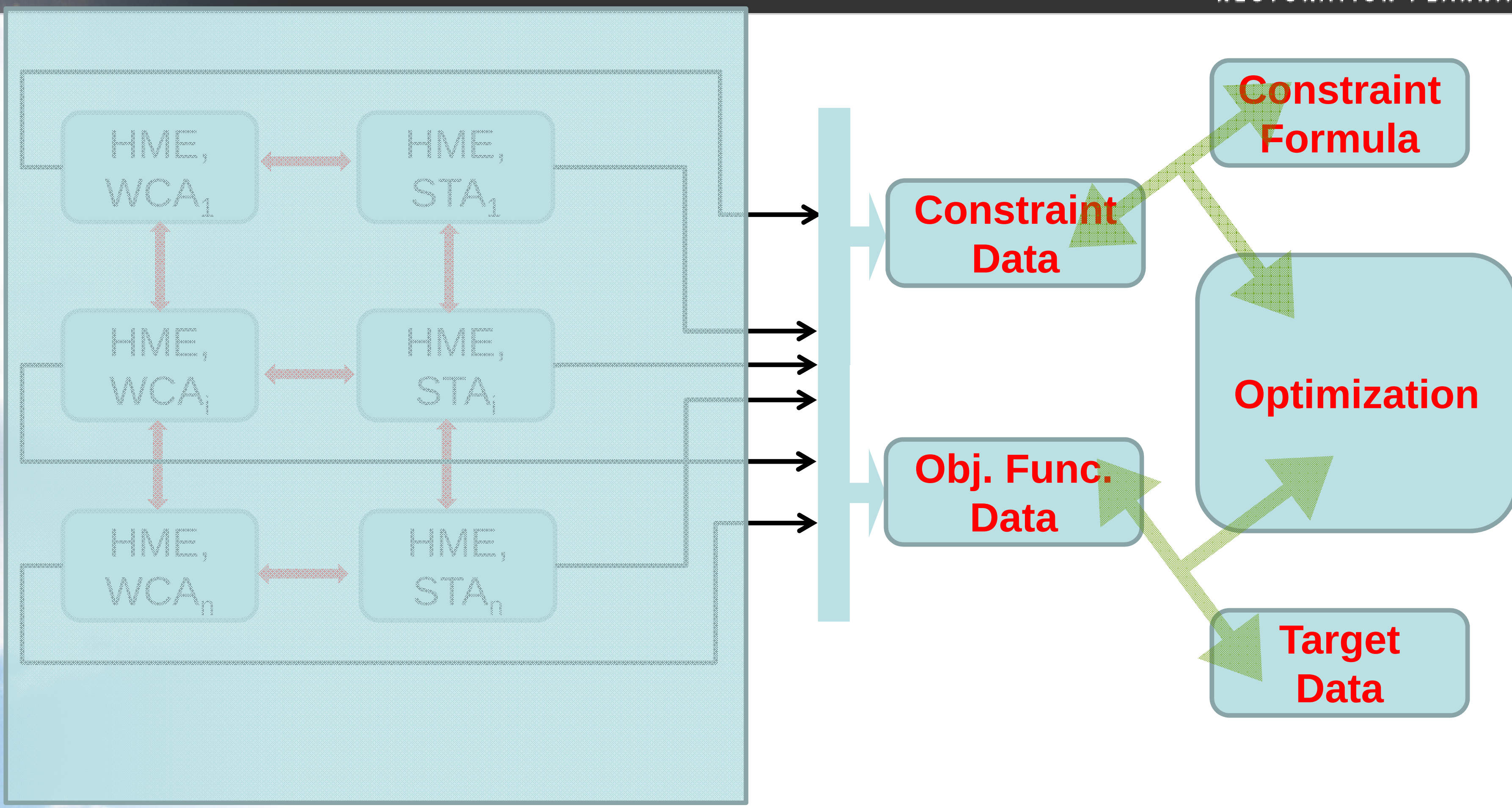


iModel Schematic



Optimization

$$\min_q f(q) \begin{cases} \Phi(q) \le 0 \\ \Psi(q) = 0 \\ A * q \le c1 \\ B * q = c2 \\ lb \le q \le ub \end{cases}$$

Objective Function and Constraints

- f(q) is the total sum of squared differences between (the desired target (Objective) and the achieved stage by the HMEs for all the 4 water bodies)

Managed System

HMEs

Desired system

RDF model

$$f(q)=\sum_{WB}\left(stage_i(q)-Target_i\right)^2$$

- Structure Capacities

$$lb \le q \le ub$$

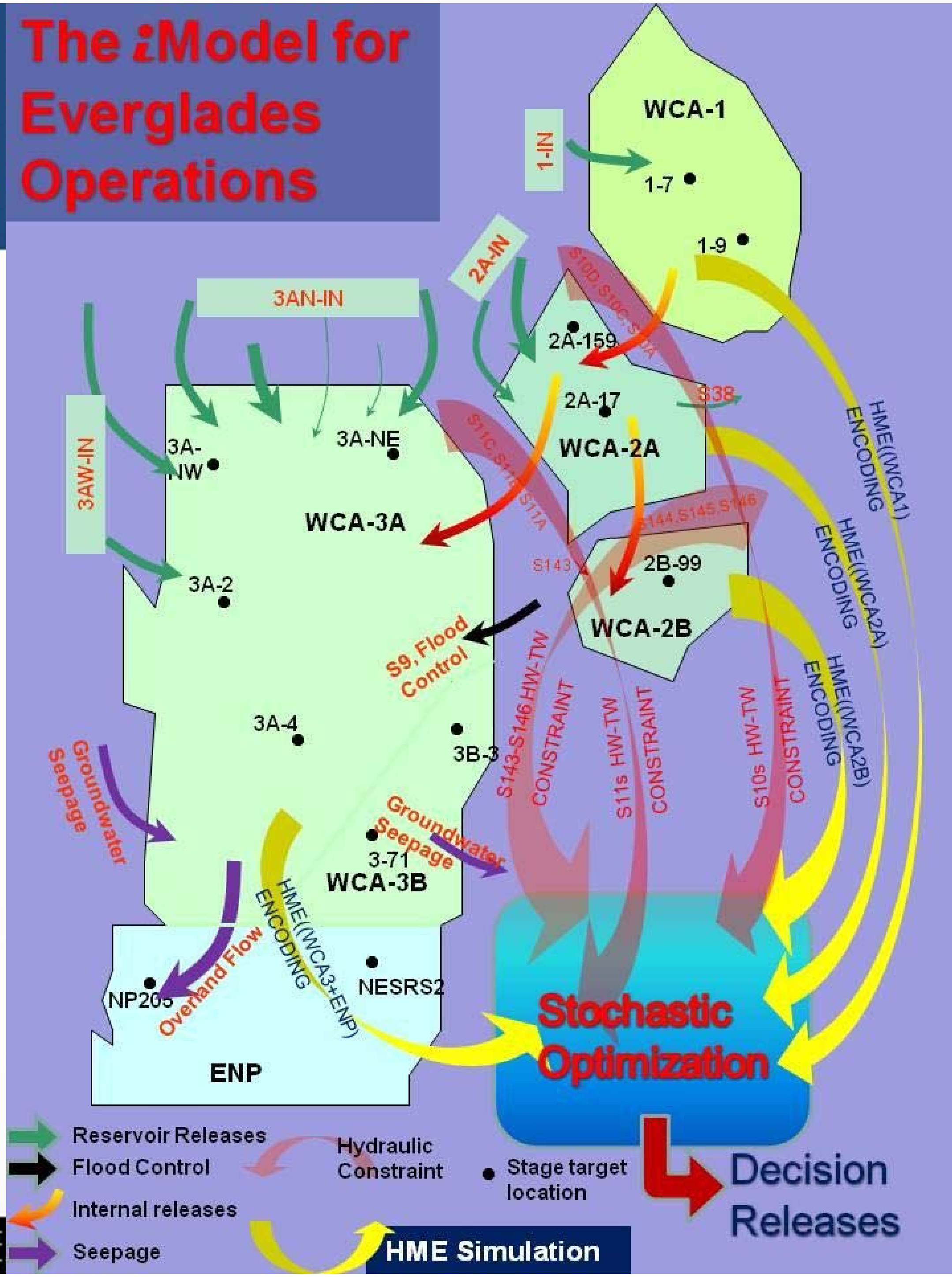
- Conveyance Capacities

$$Q_{\max}-\alpha*(H_w-T_w)^{\beta}\le 0$$

$$Q_{\max}-\alpha*(HME_{Hw,Tw})^{\beta}\le 0$$

The basic genetic algorithm

- Start with a large "population" of randomly generated
  "attempted solutions" to a problem
- Repeatedly do the following:
  - Evaluate each of the attempted solutions
  - Keep a subset of these solutions (the "best" ones)
  - Use these solutions to generate a new population
- Quit when you have a satisfactory solution (or you run out of time)

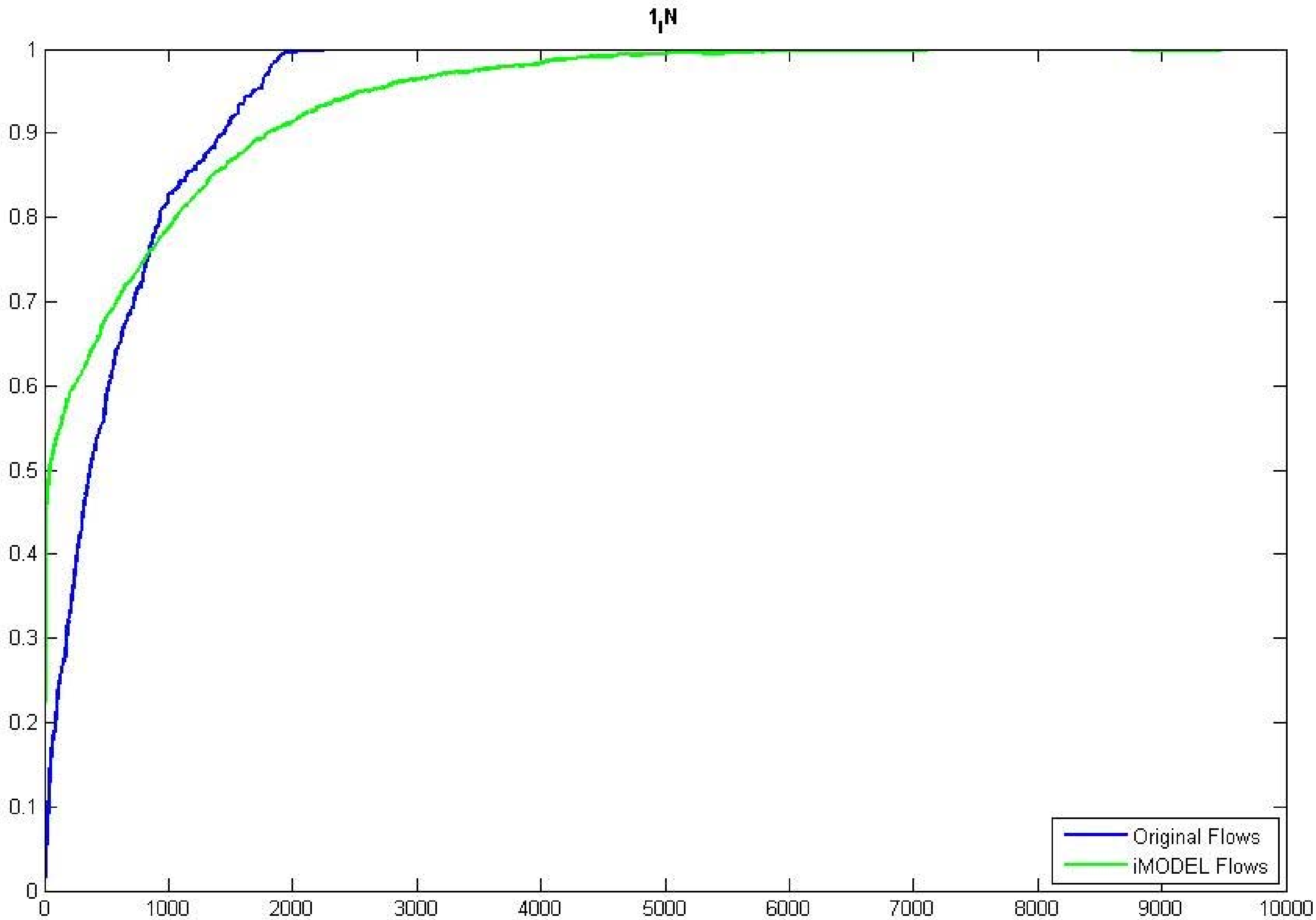


The ¿Model for Everglades Operations
WCA-1
1-IN
1-7
1-9
2A-IN
3AN-IN
3AW-IN
S10D, S10C, S10A
2A-159
2A-17
S38
WCA-2A
3A-NW
3A-NE
WCA-3A
S11C, S11B, S11A
S144,S145,S146
S143
2B-99
WCA-2B
3A-2
S9, Flood Control
HME(WCA1) ENCODING
HME(WCA2A) ENCODING
HME(WCA2B) ENCODING
S143-S146 HW-TW CONSTRAINT
S11s HW-TW CONSTRAINT
S10s HW-TW CONSTRAINT
3A-4
3B-3
Groundwater Seepage
Groundwater Seepage
3-71
WCA-3B
HME(WCA3+ENP) ENCODING
Overland Flow
NP205
NESRS2
ENP
Stochastic Optimization
Decision Releases
Reservoir Releases
Flood Control
Internal releases
Seepage
Hydraulic Constraint
Stage target location
HME Simulation

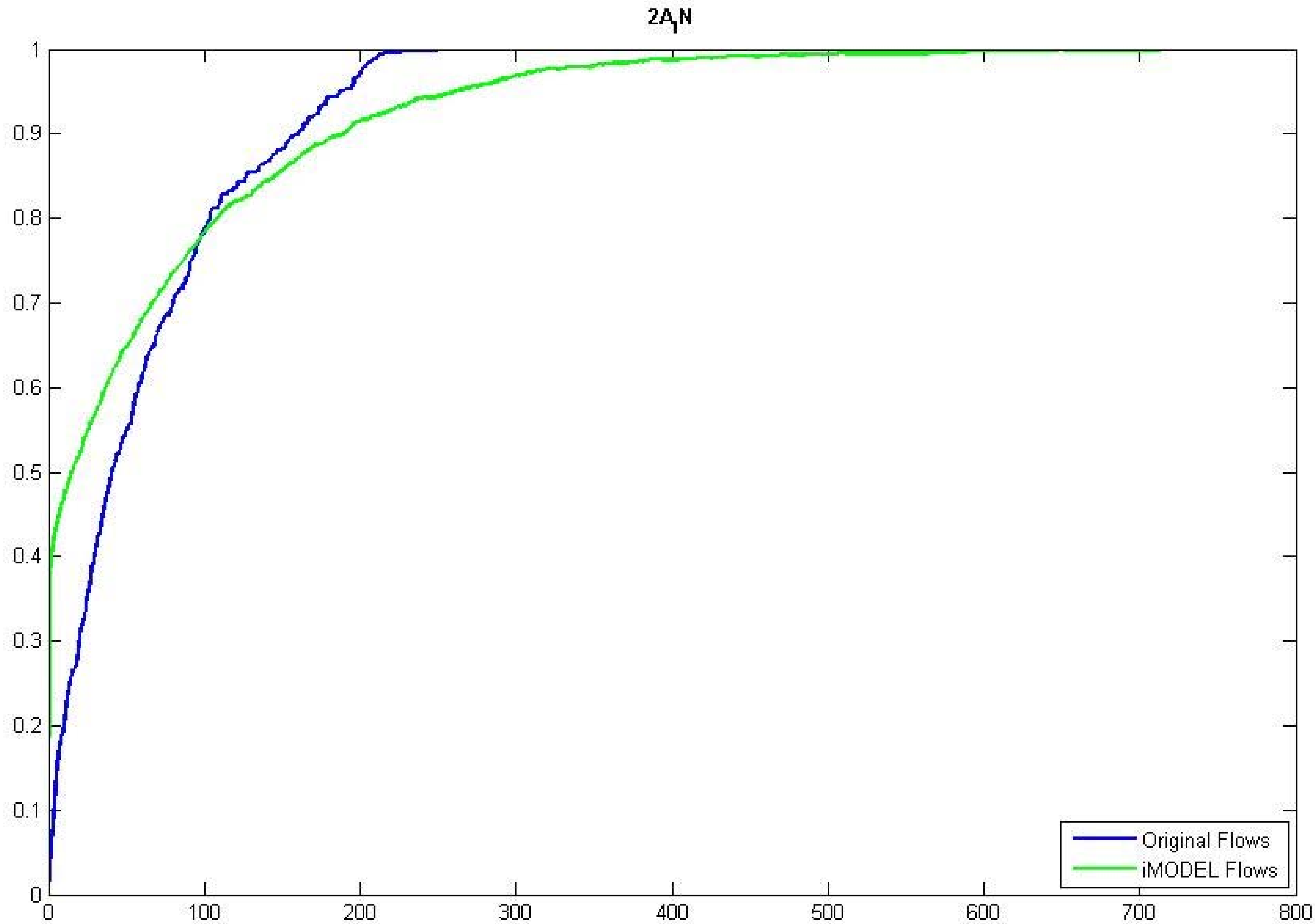
FLOW COMPARISONS

- Original flow from RSM
- iModel optimal flows

Original flow and iModel flow duration curve



Original flow and iModel flow duration curve



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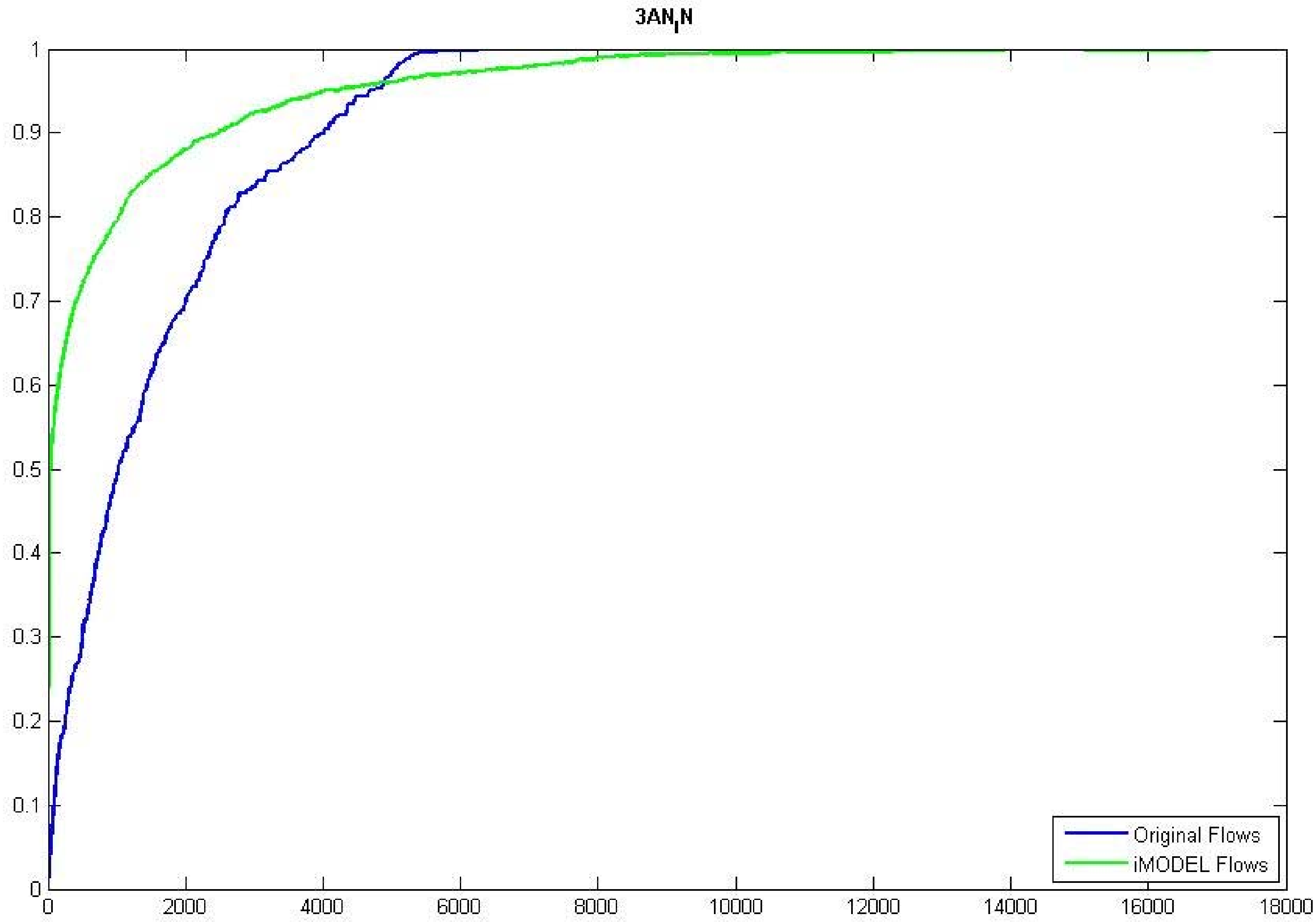

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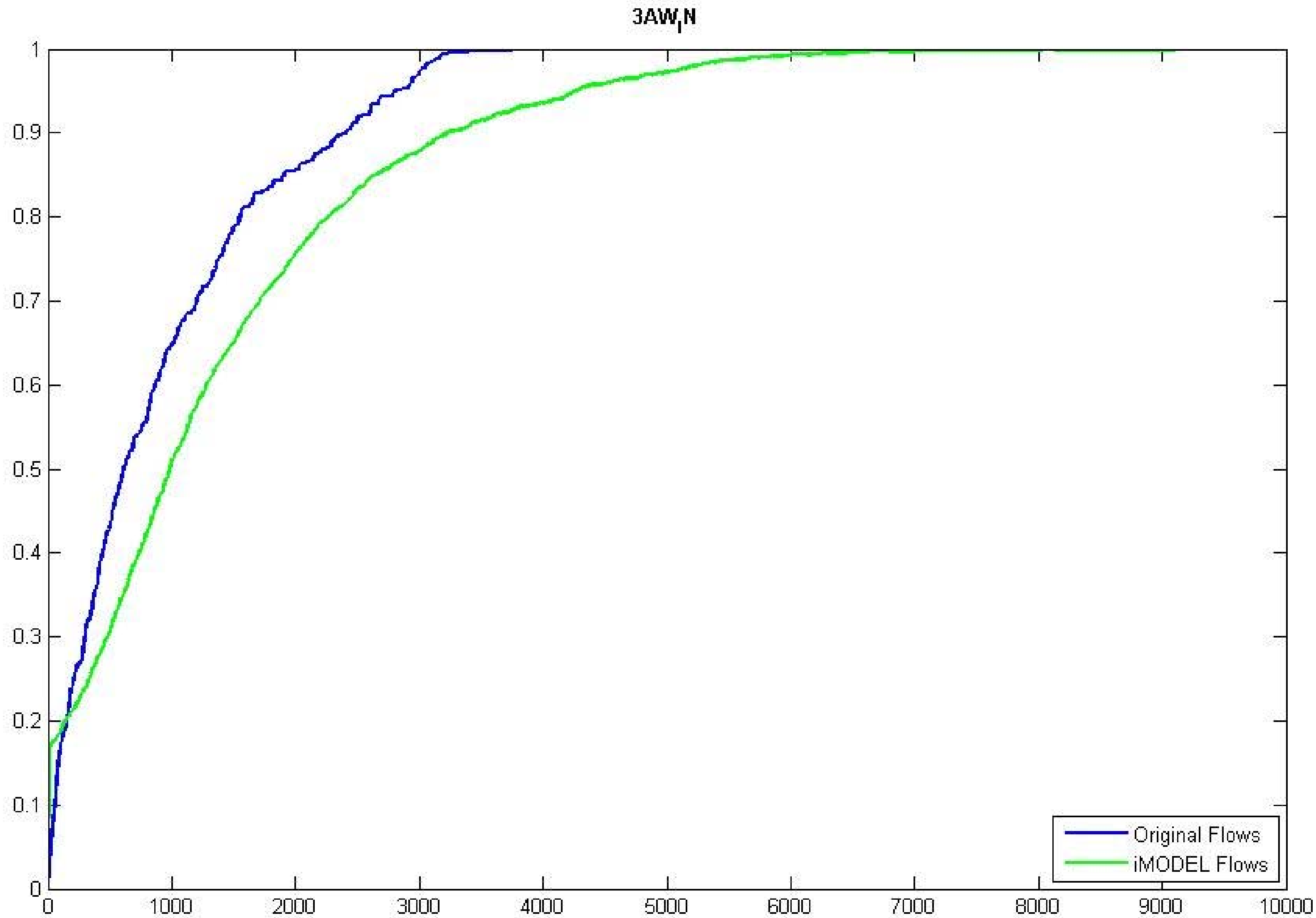

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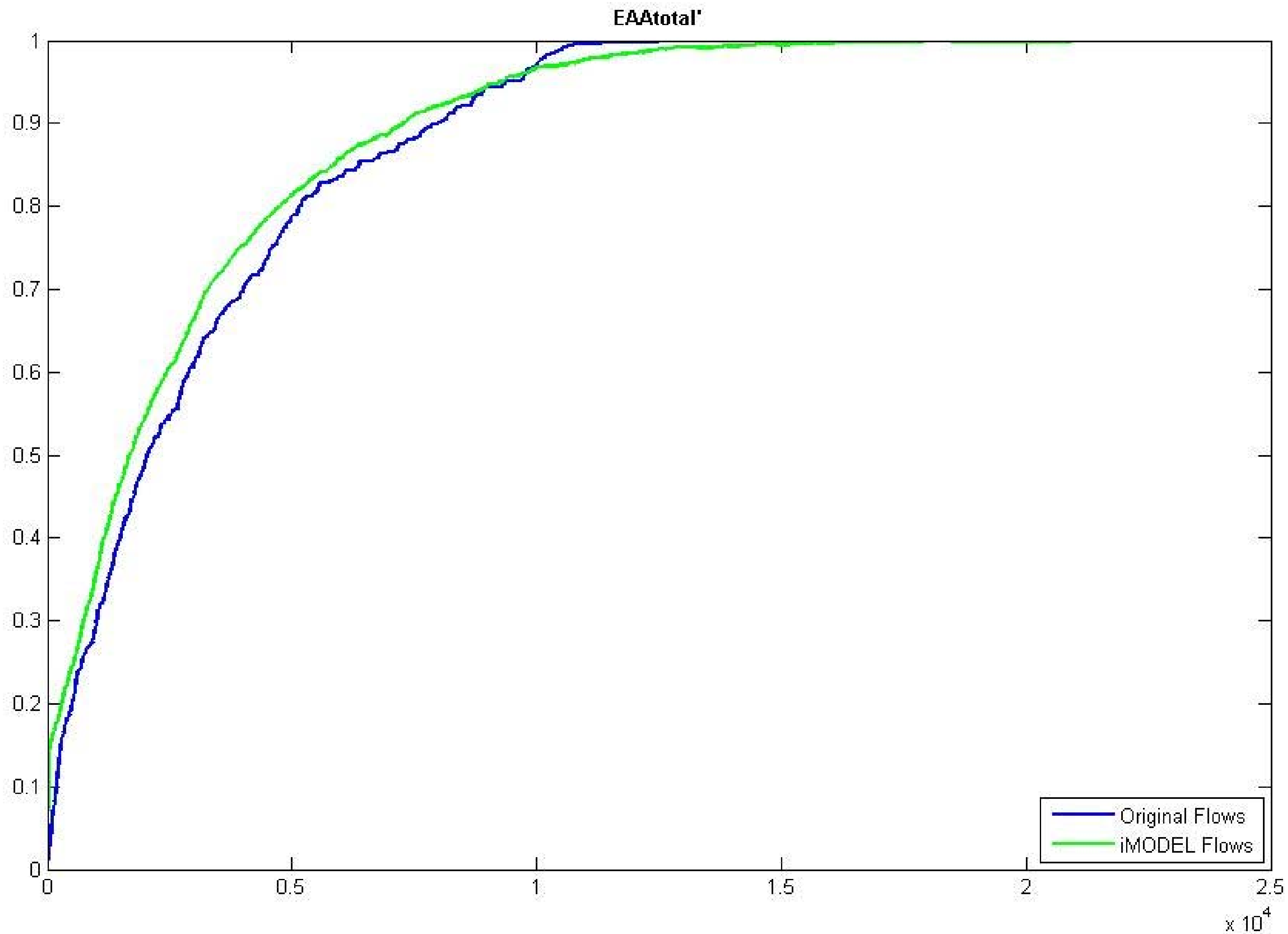
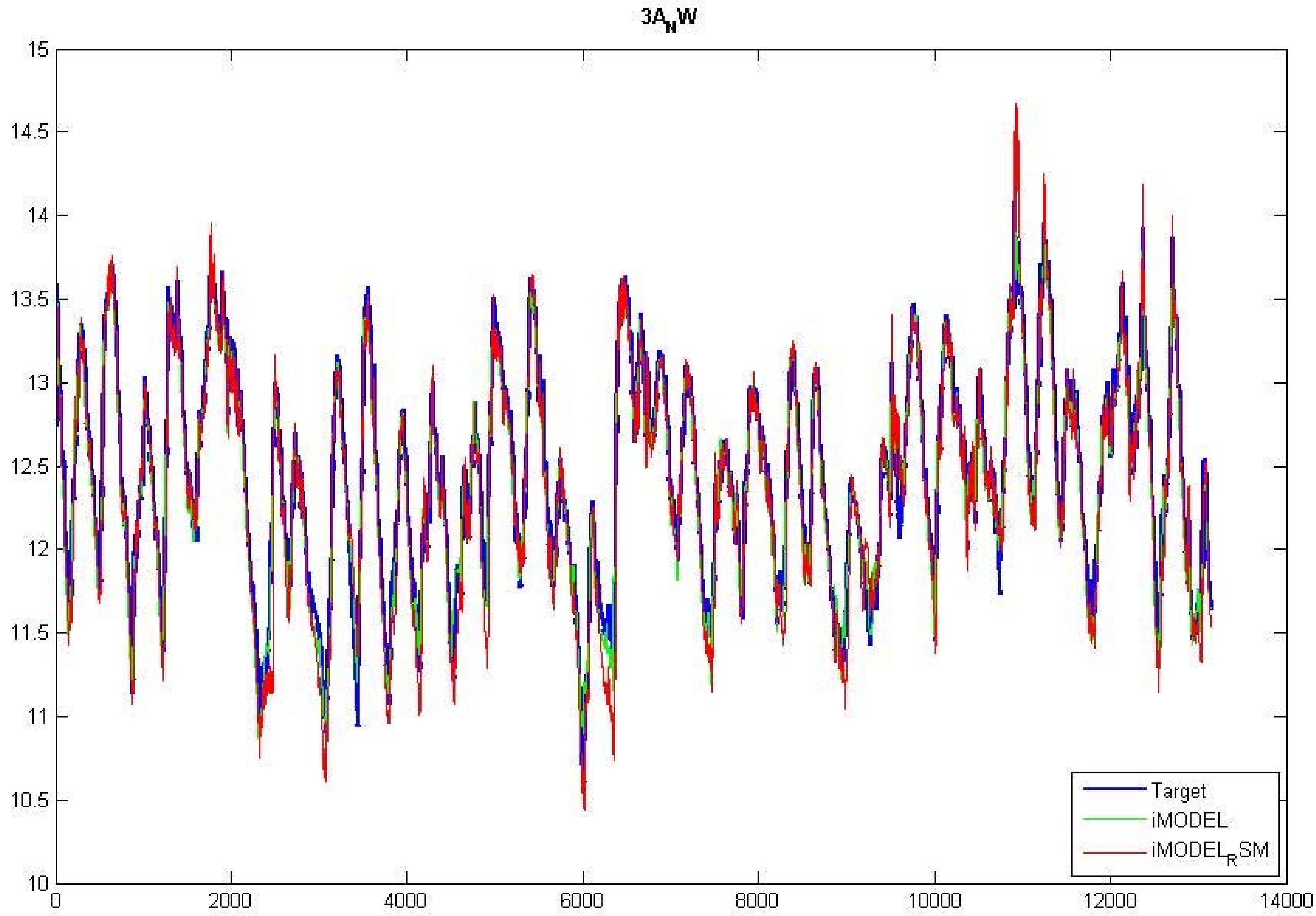


STAGE COMPARISONS

- Stage target
- iModel achieved stage
- RSM simulated stage based on iModel optimal flows.

Target, iModel, RSM daily simulated stage



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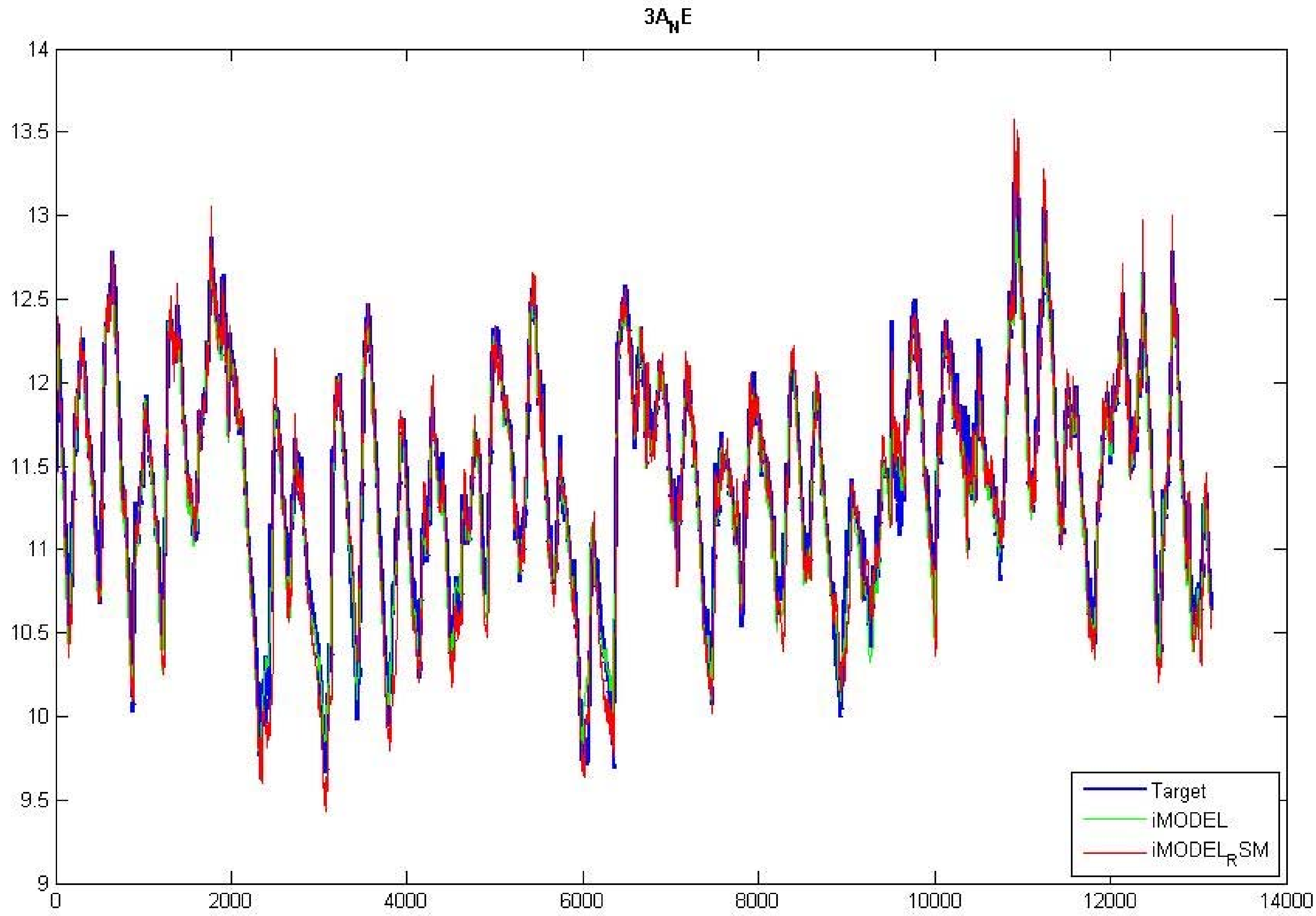
Target, iModel, RSM daily simulated stage



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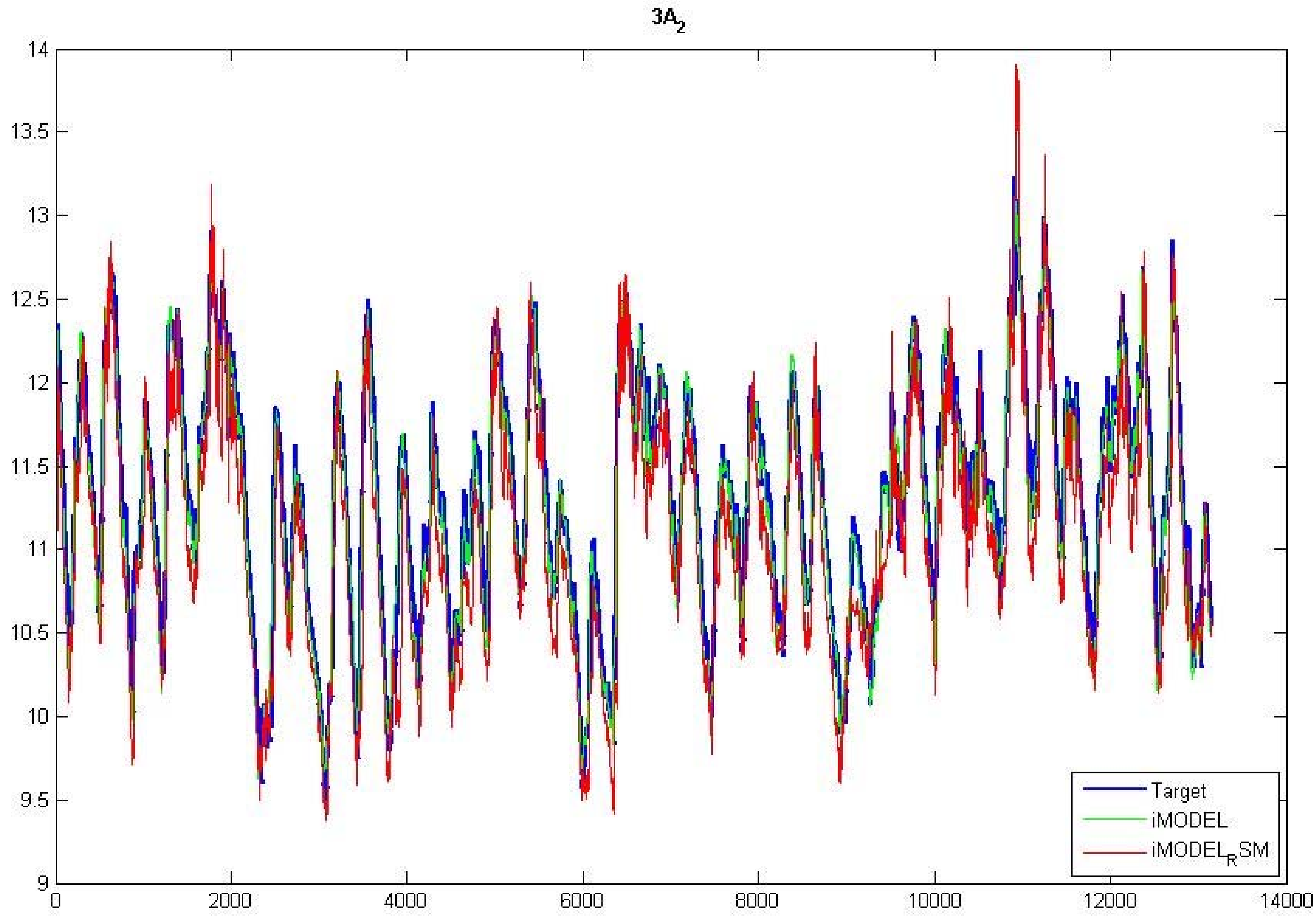

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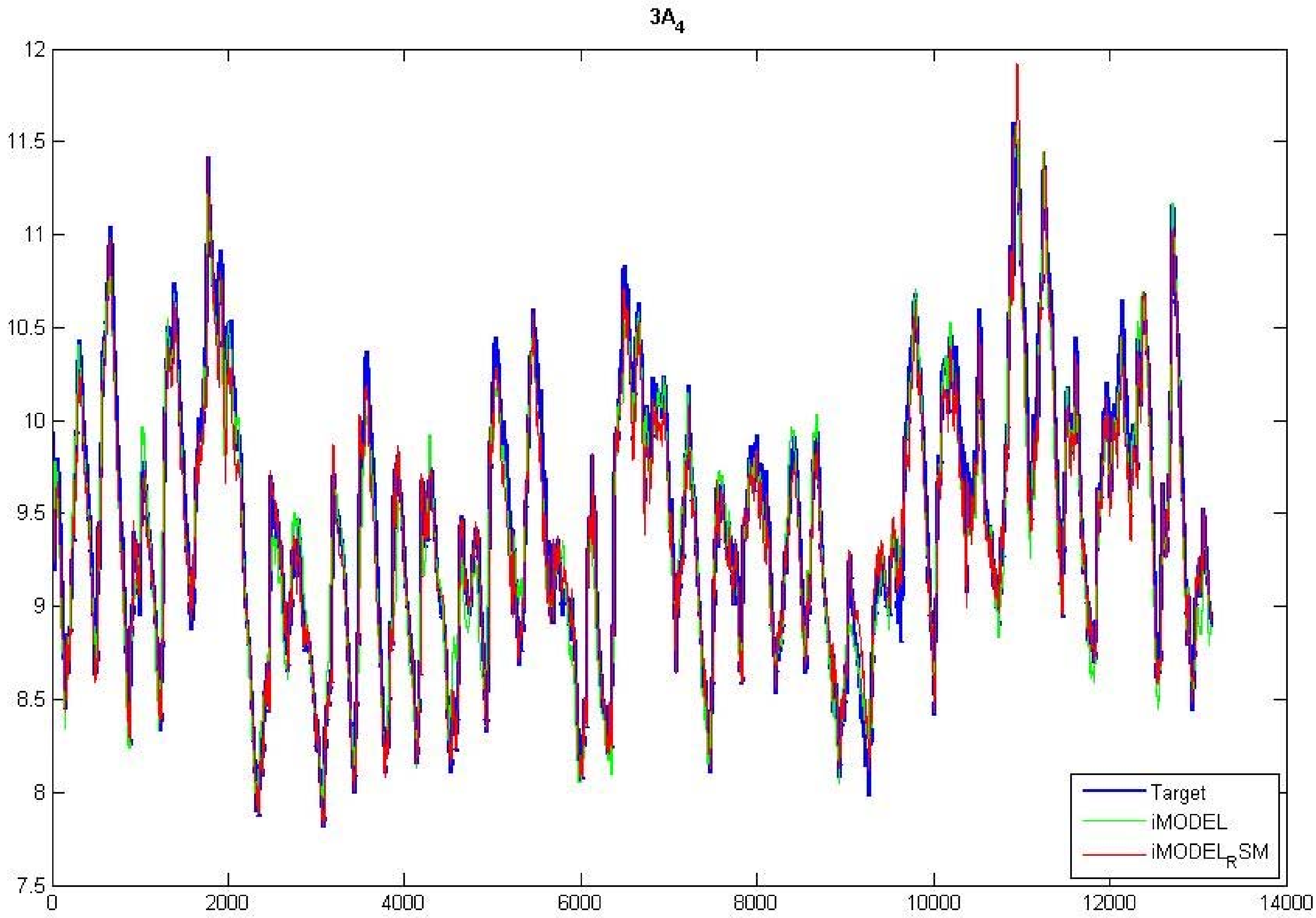

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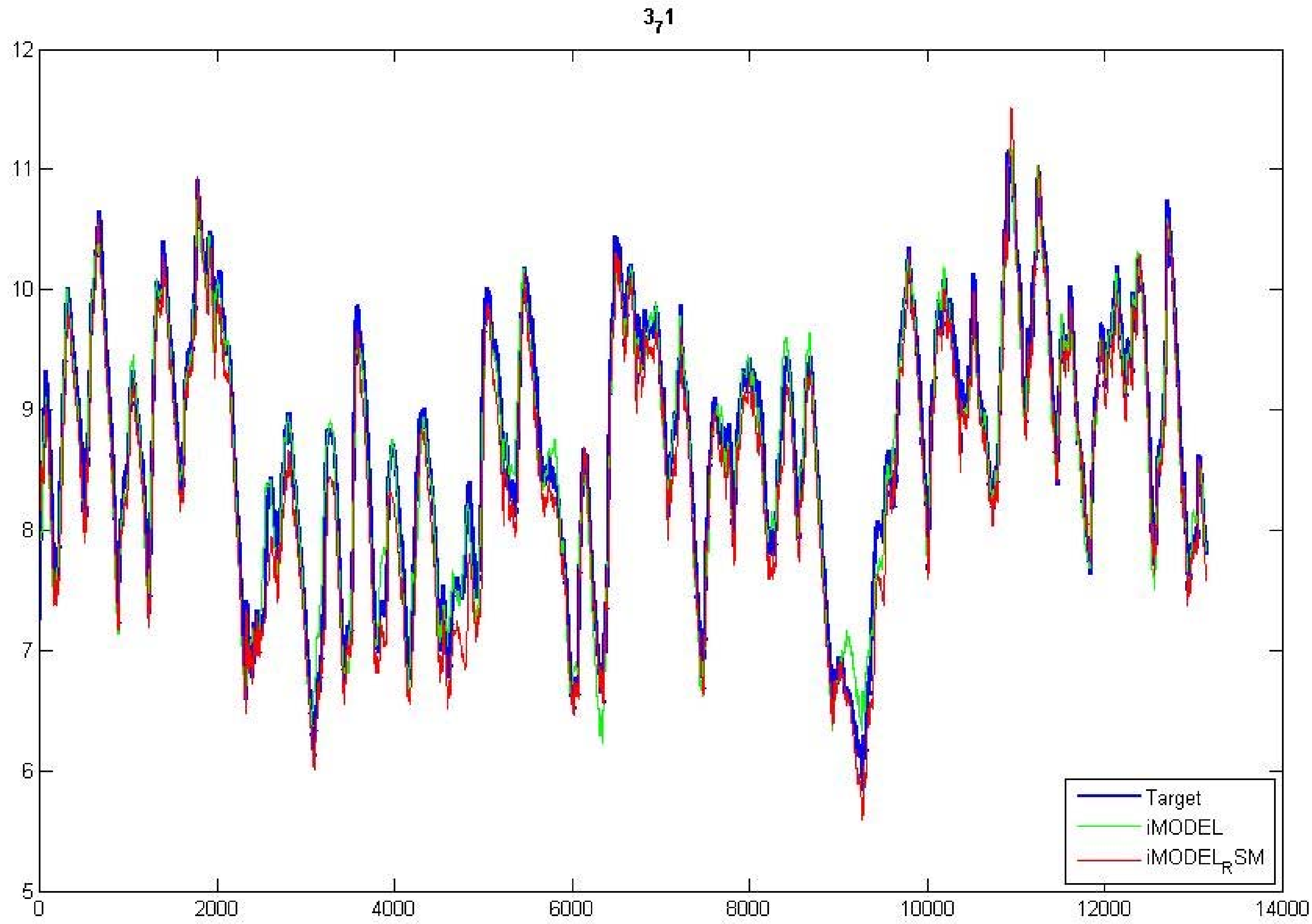

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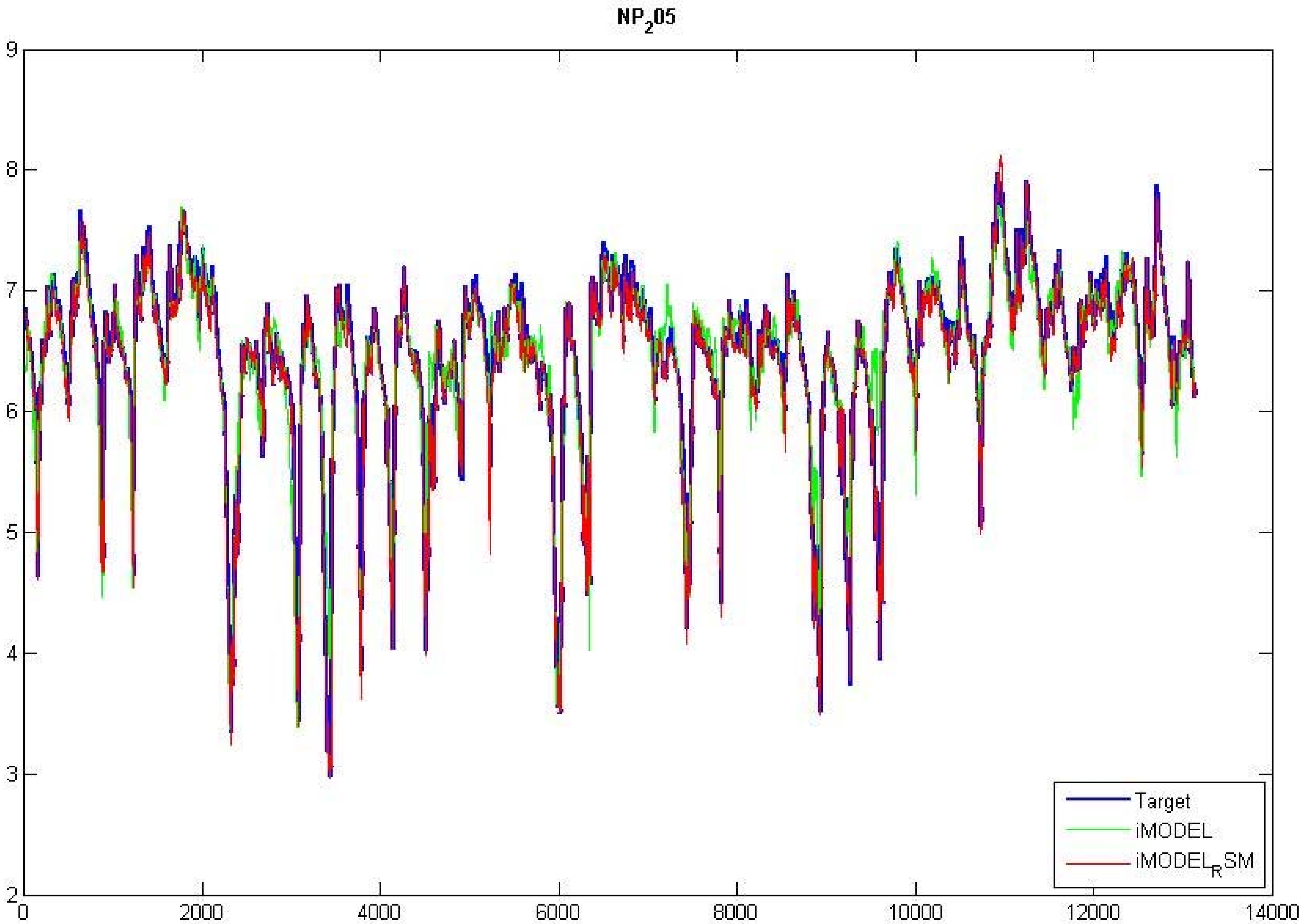

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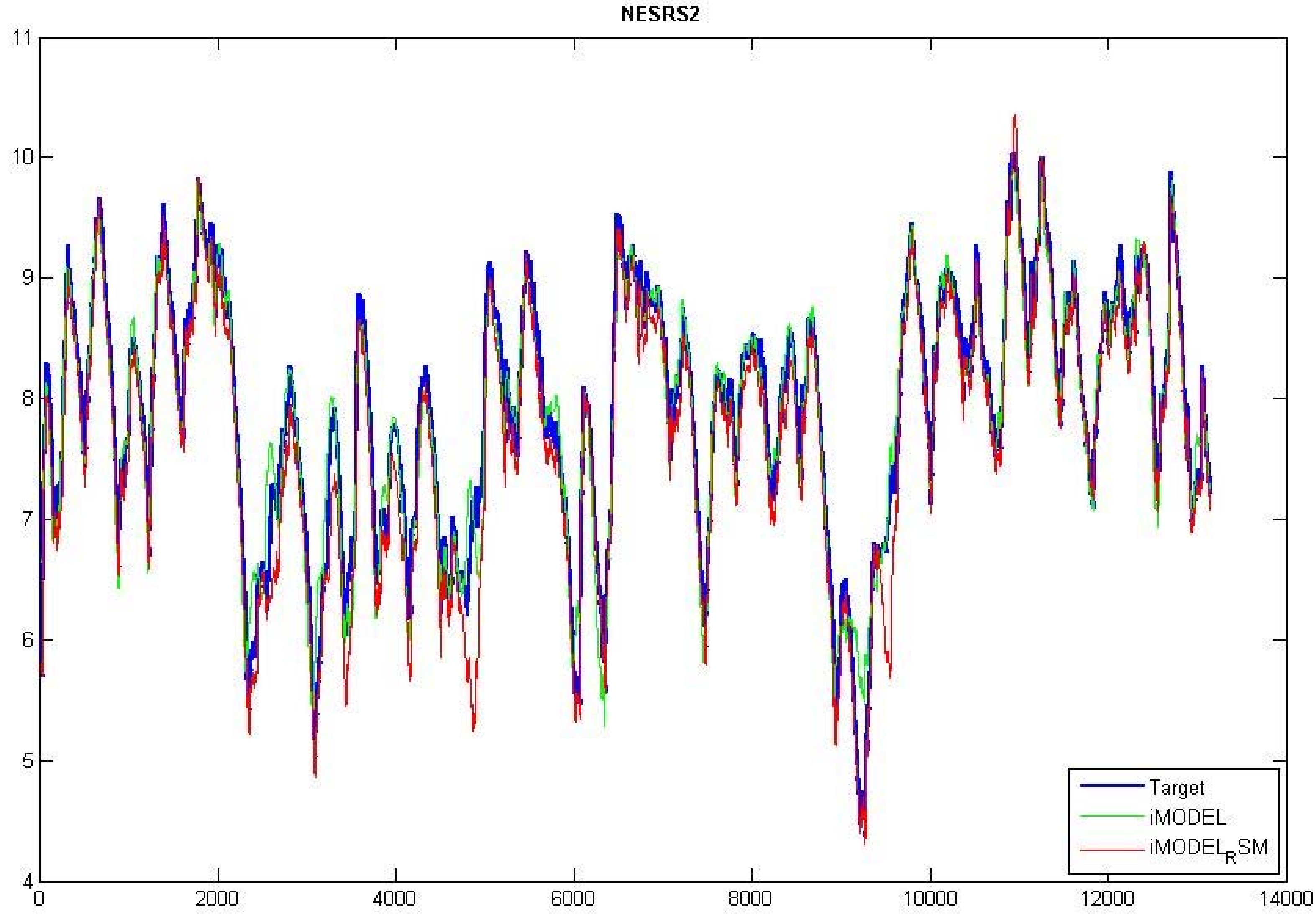

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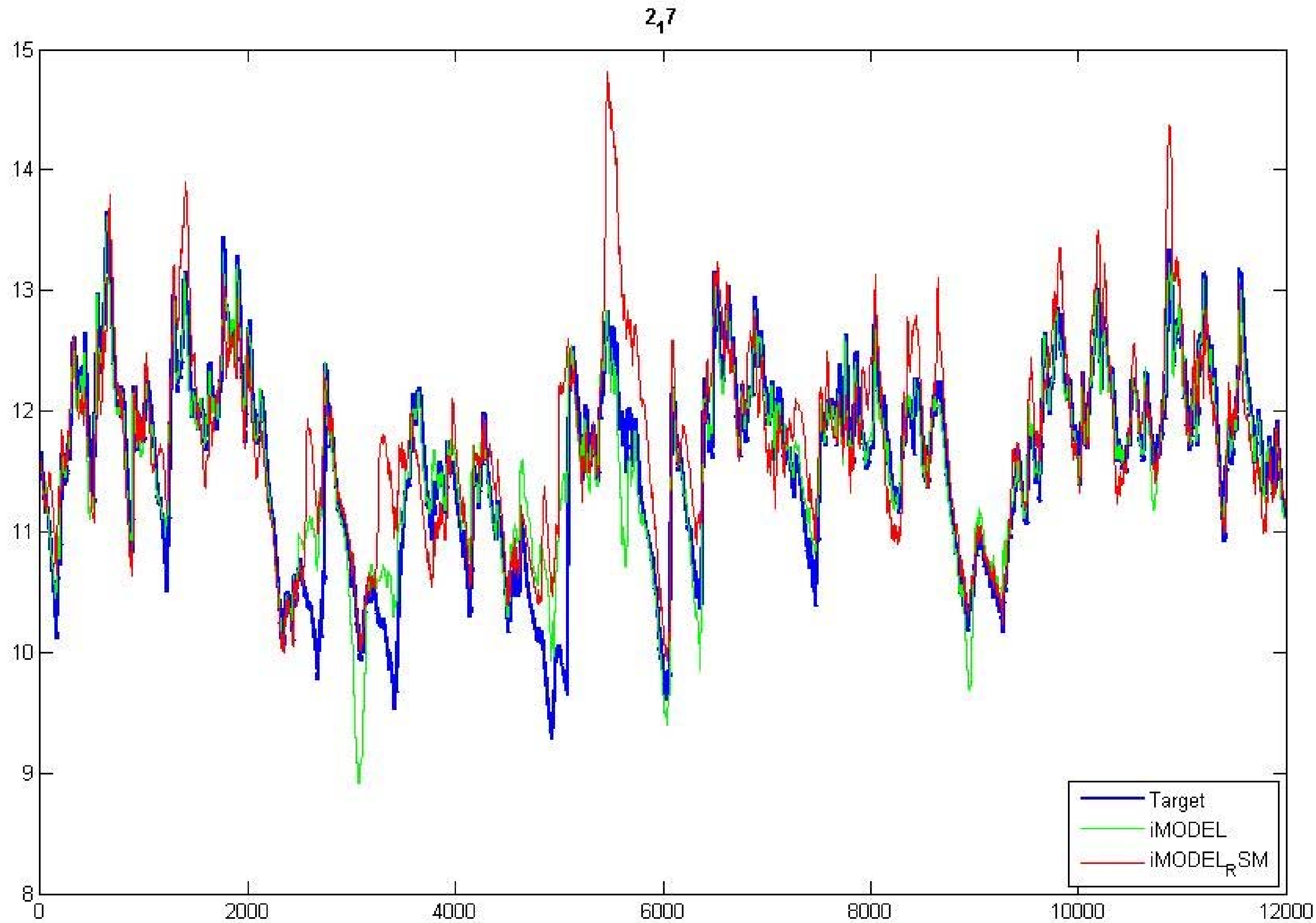
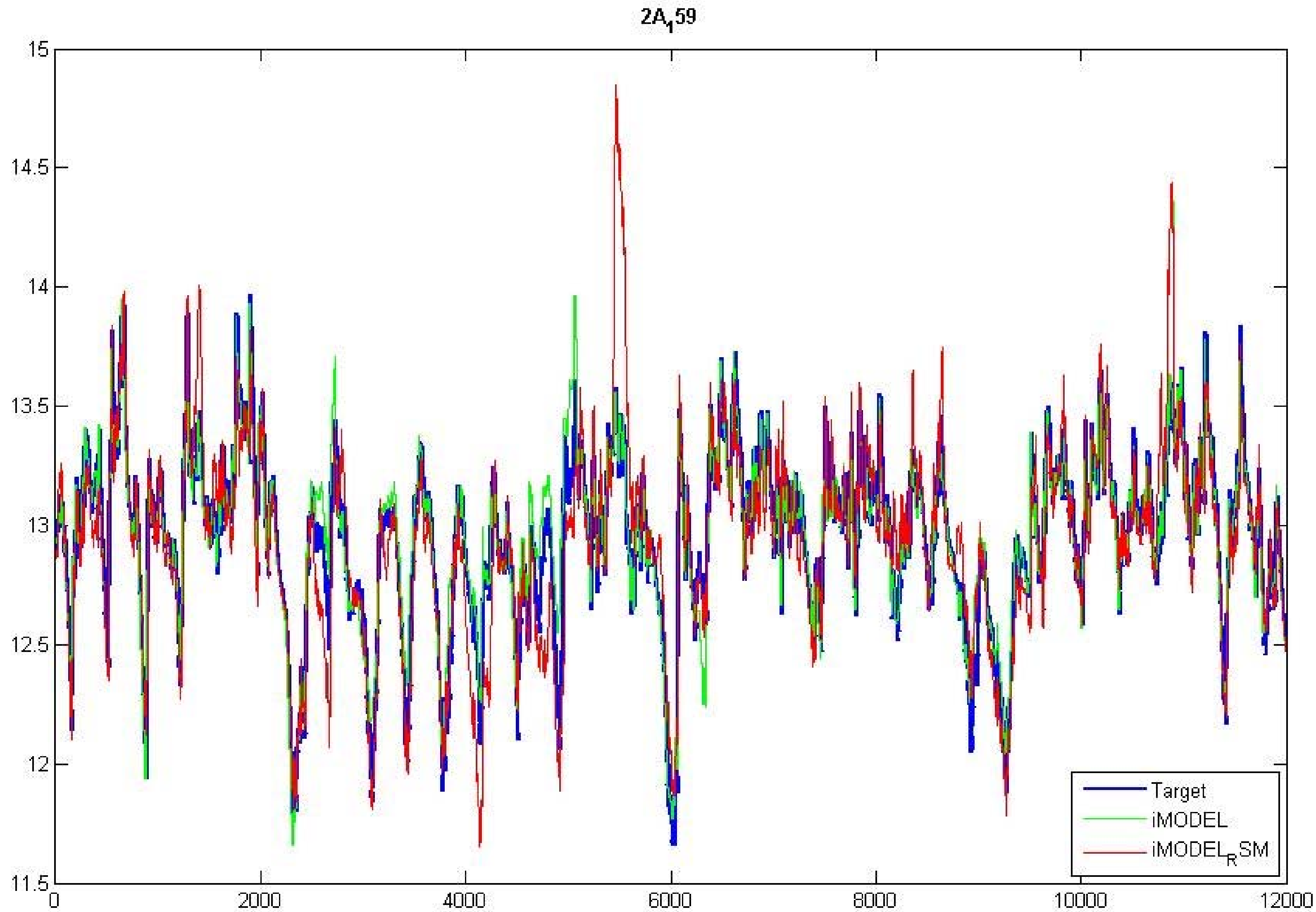


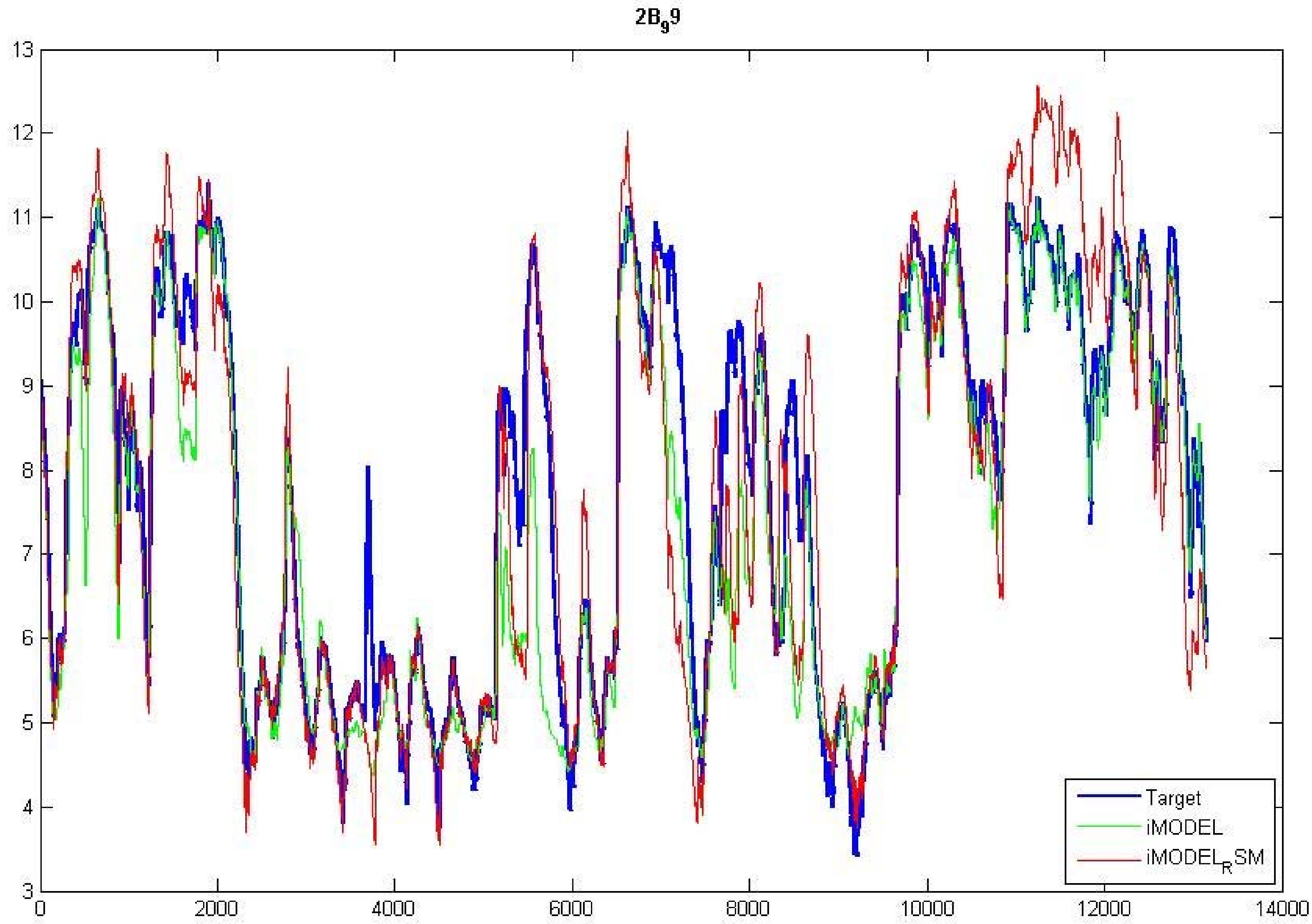
Keeplimits*

Target, iModel, RSM daily simulated stage



Target, iModel, RSM daily simulated stage

Keepinmits



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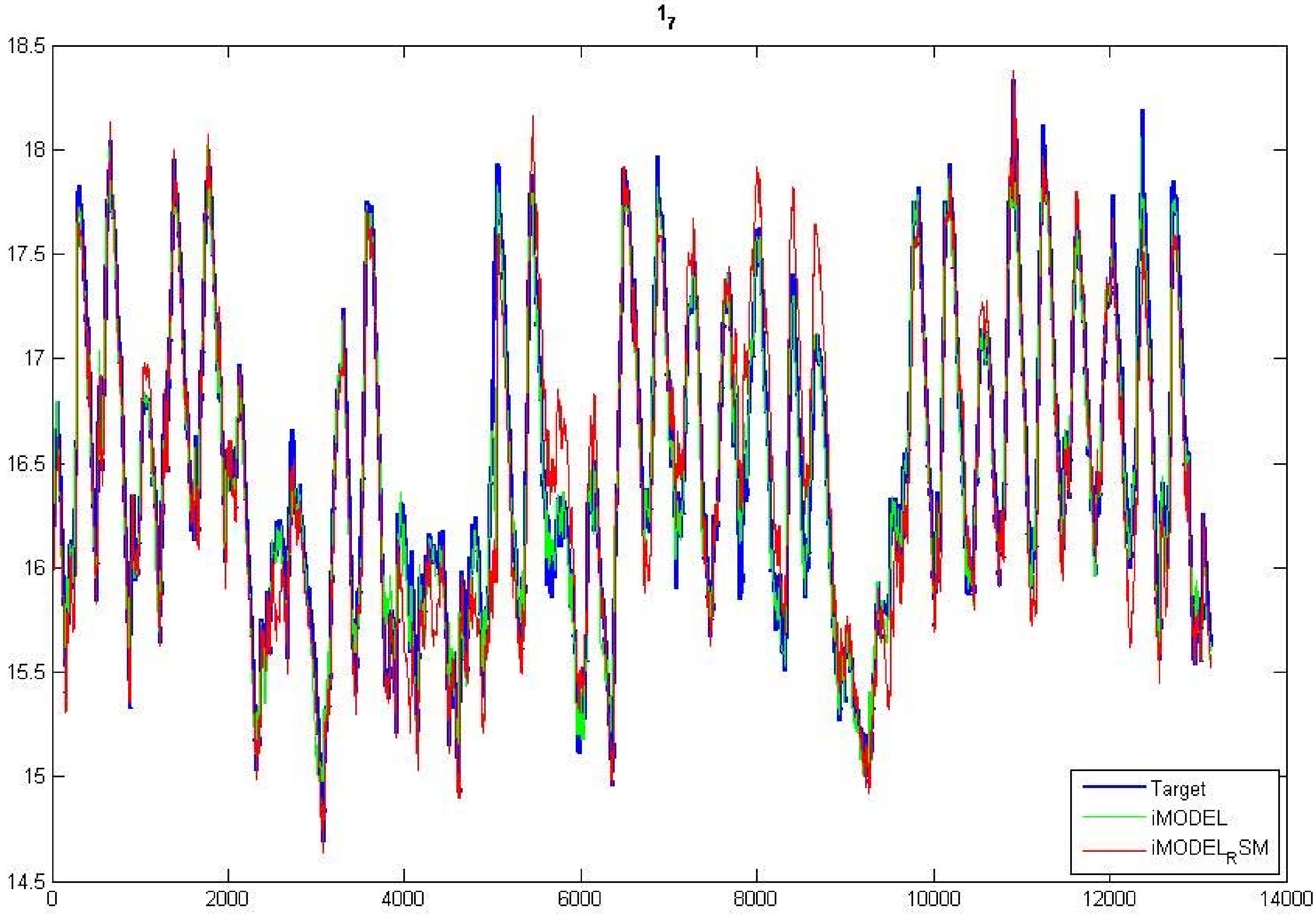

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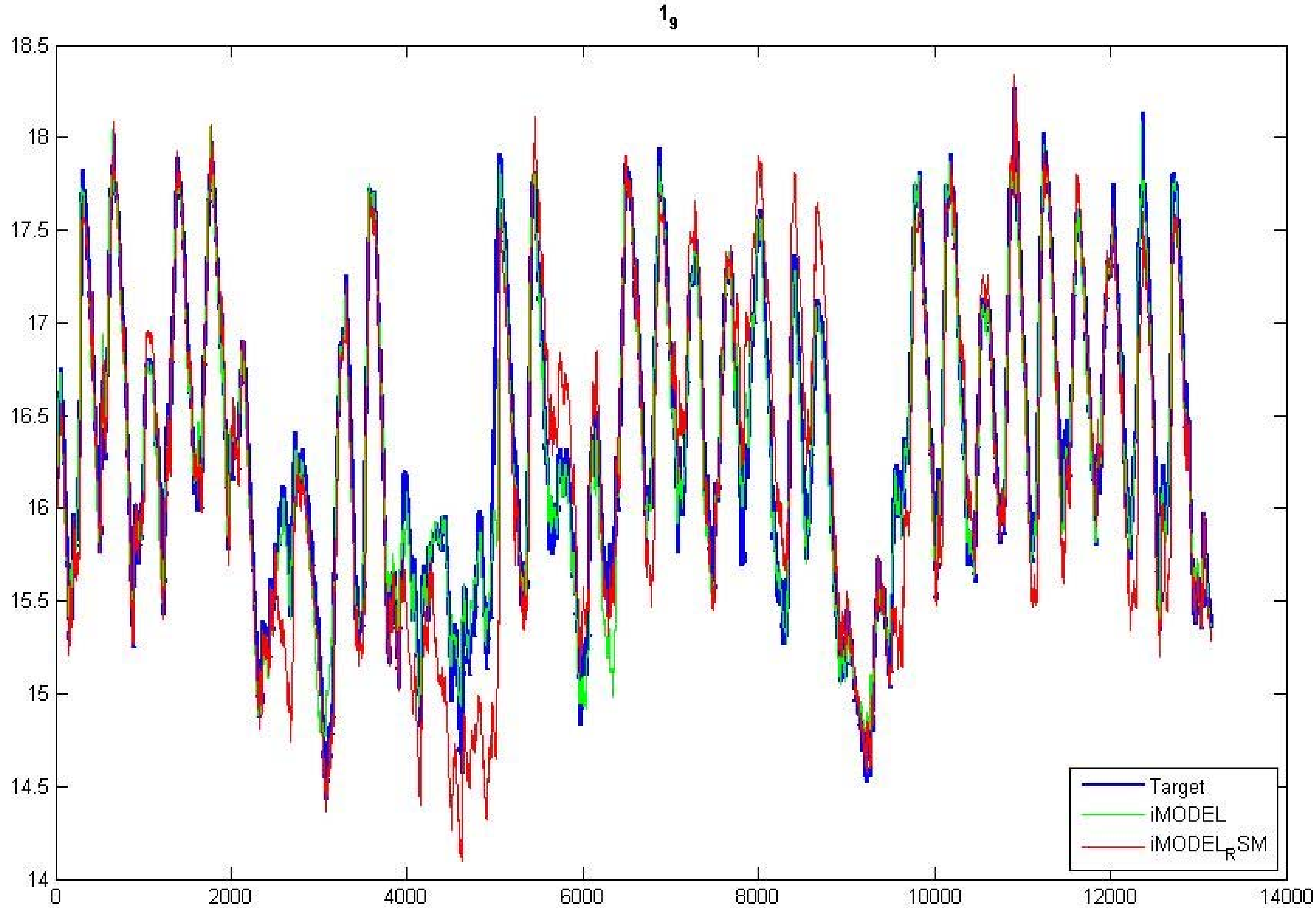
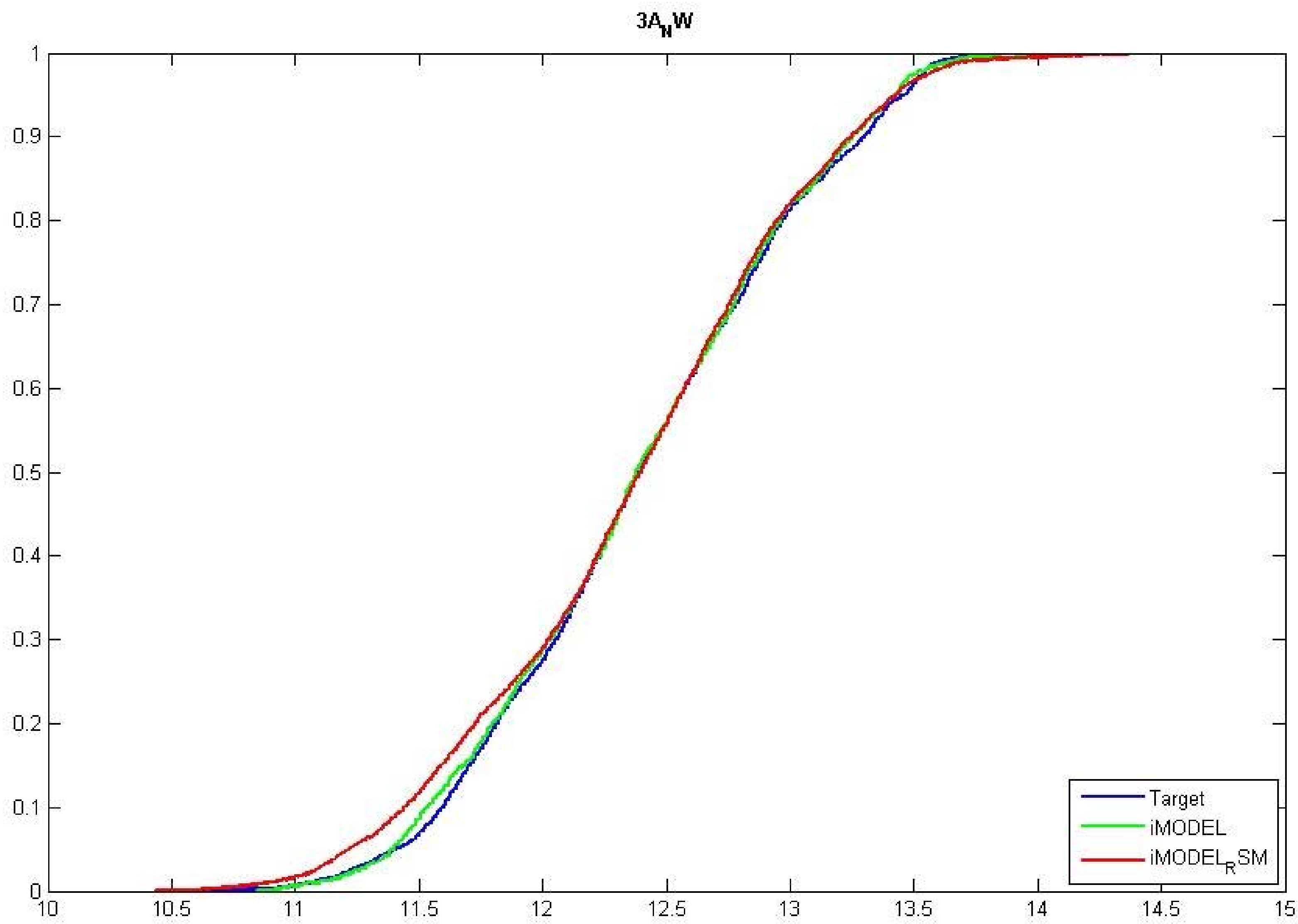


Target, iModel, RSM stage duration curve



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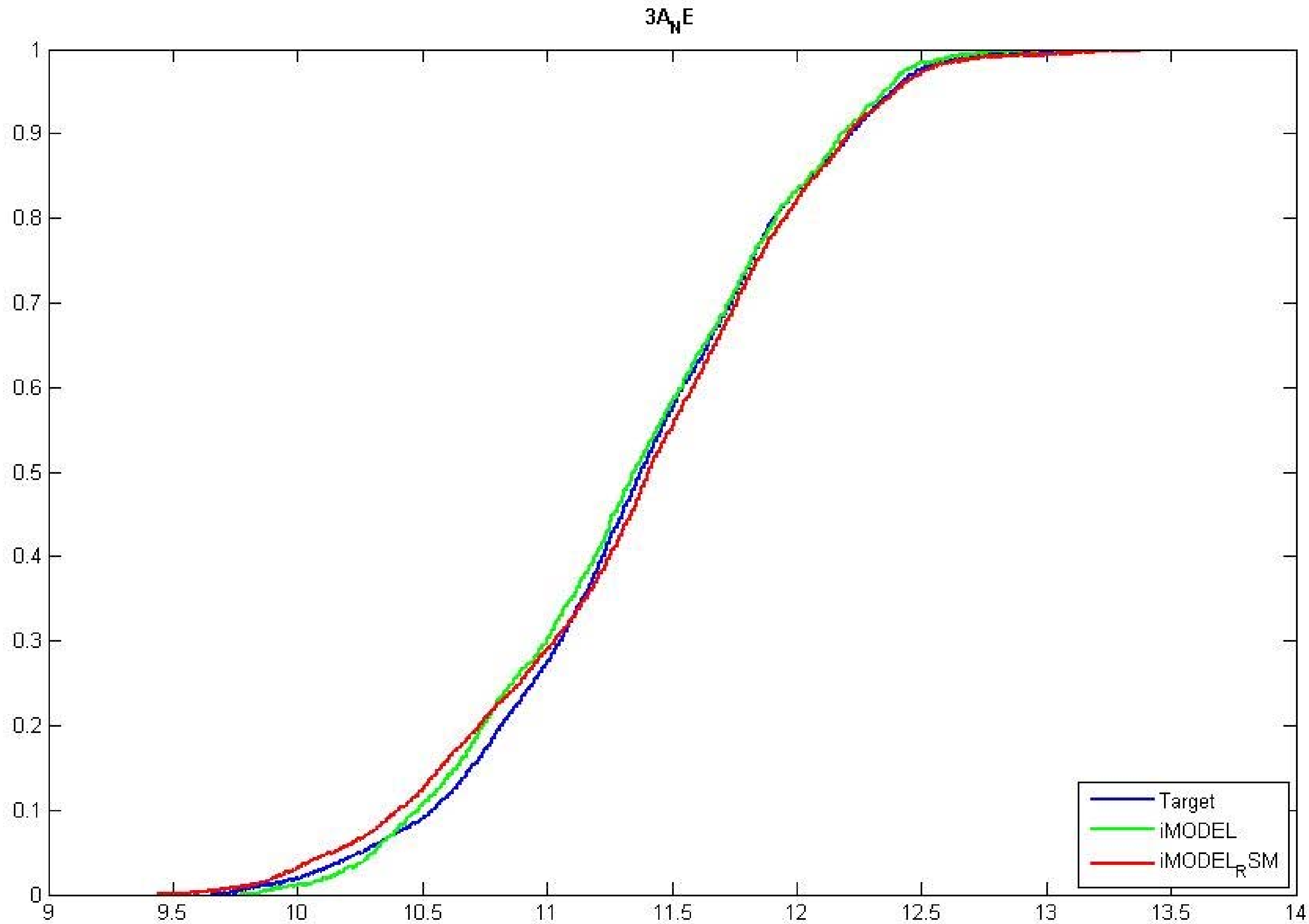

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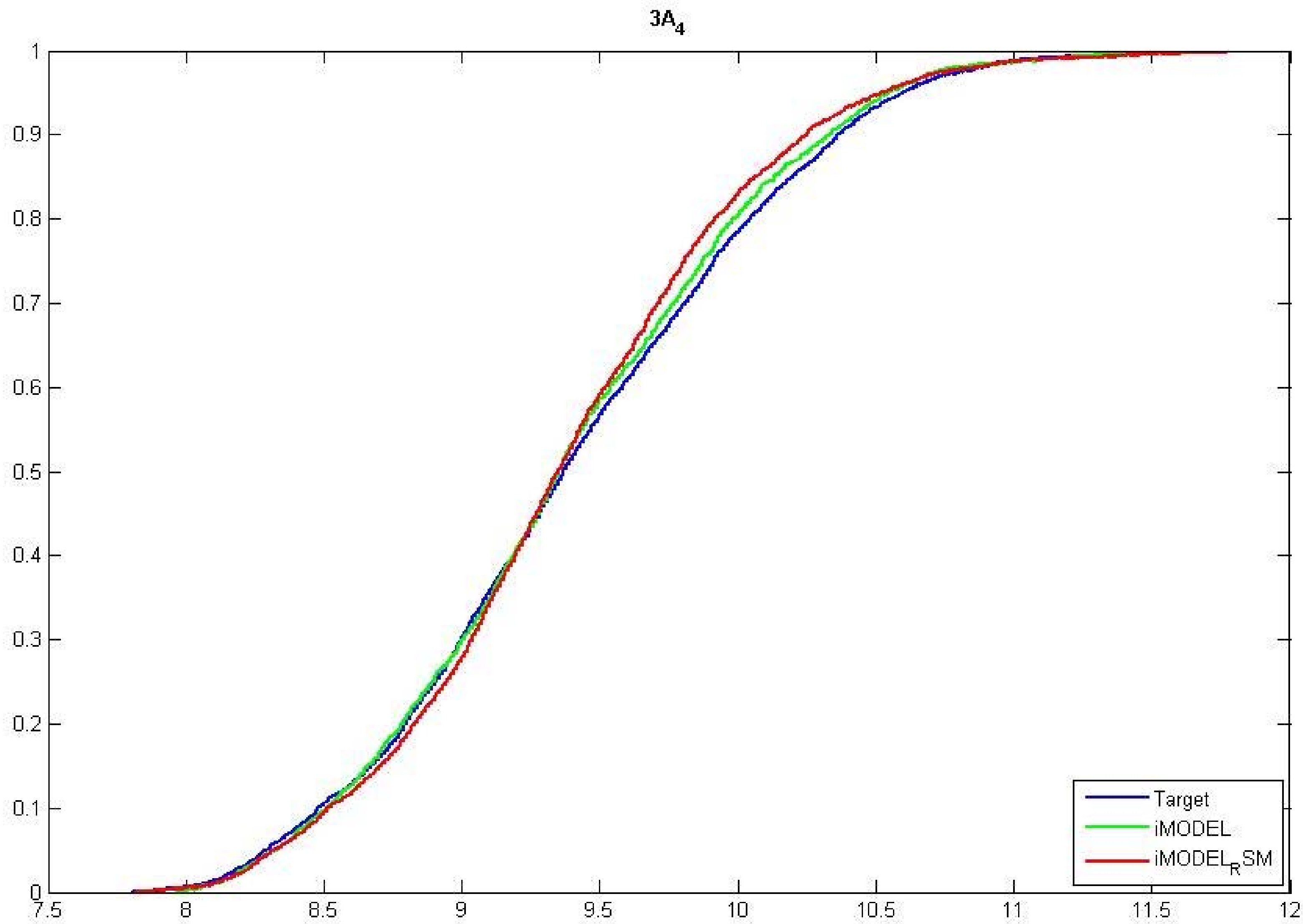

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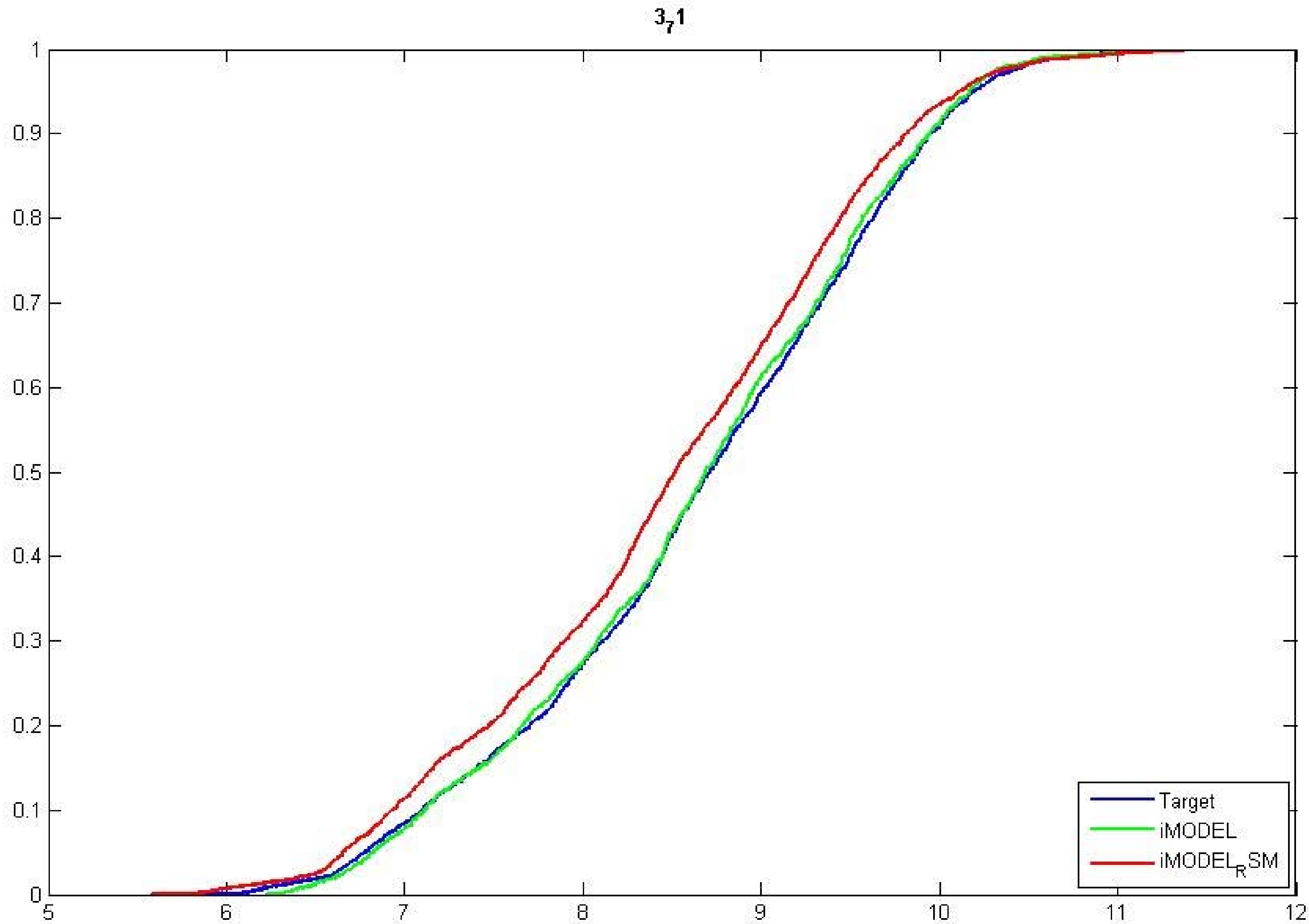

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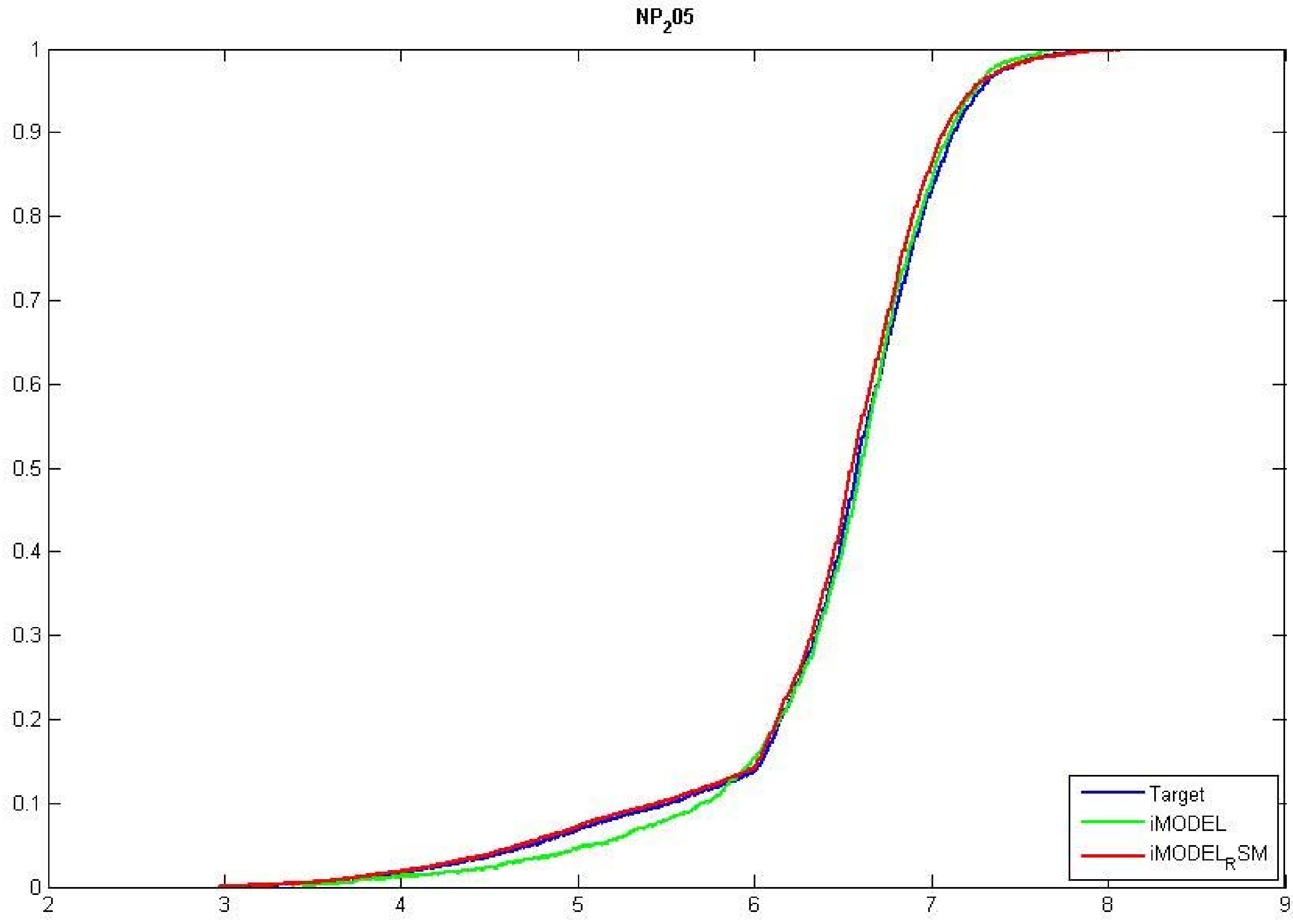

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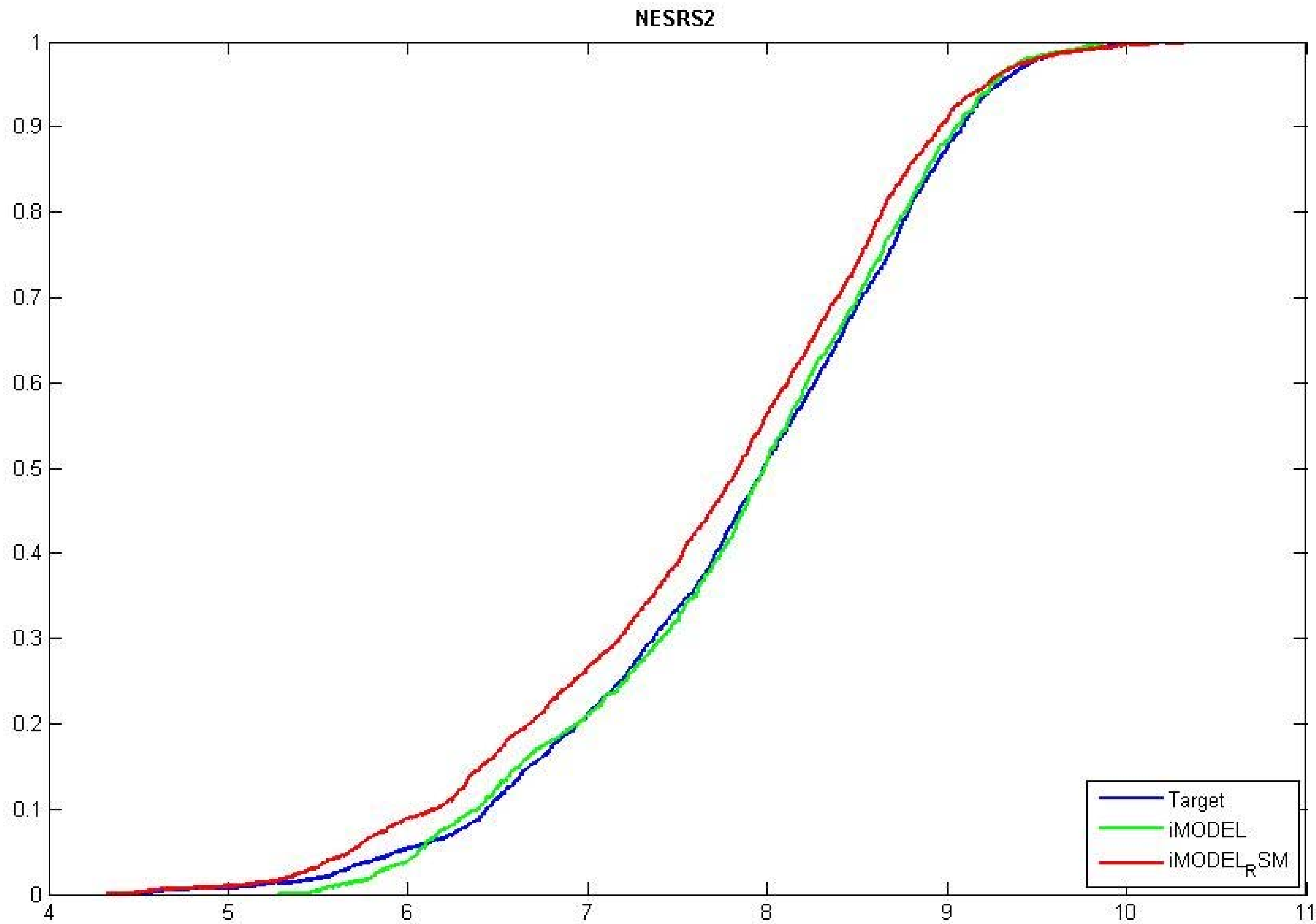

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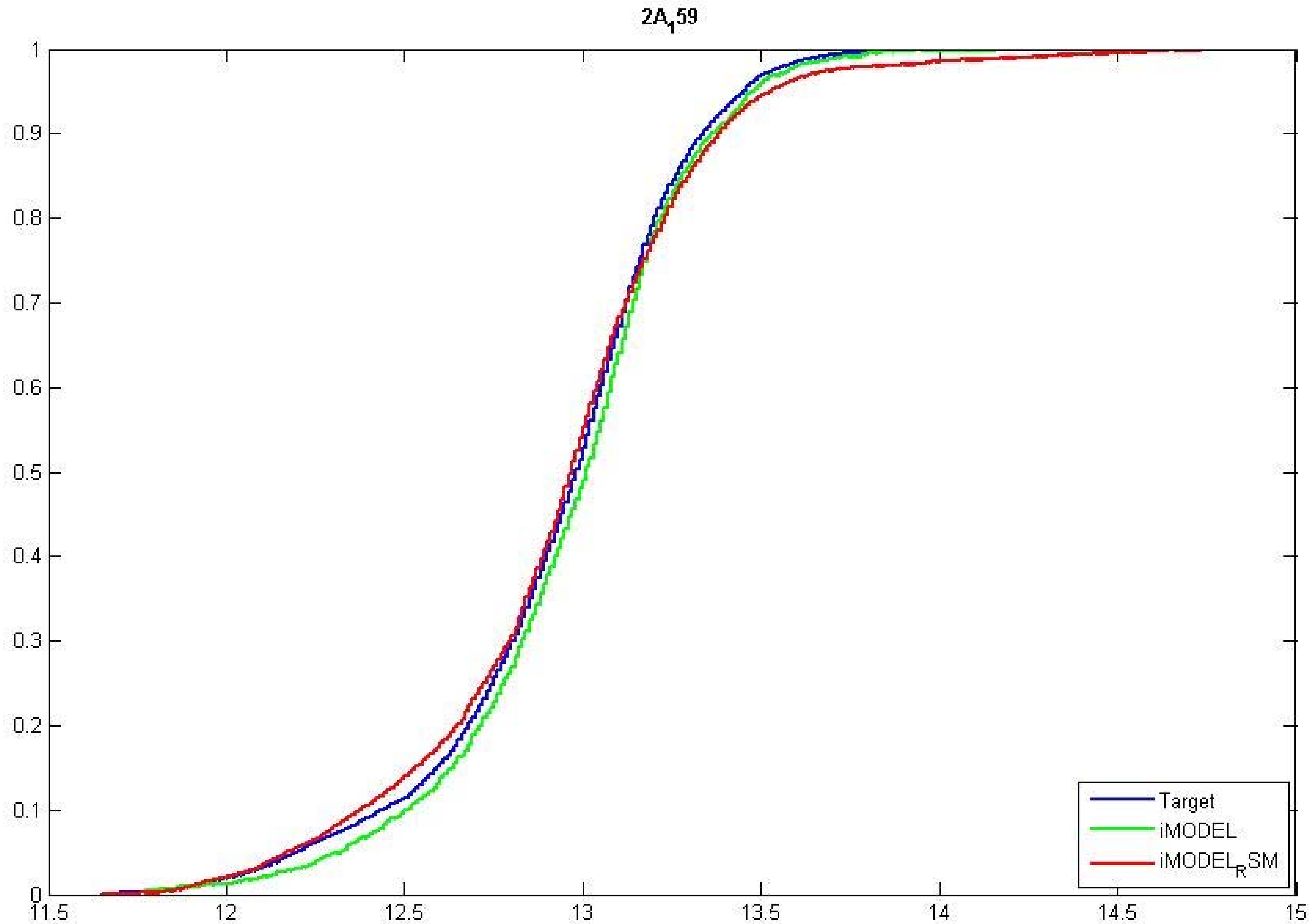

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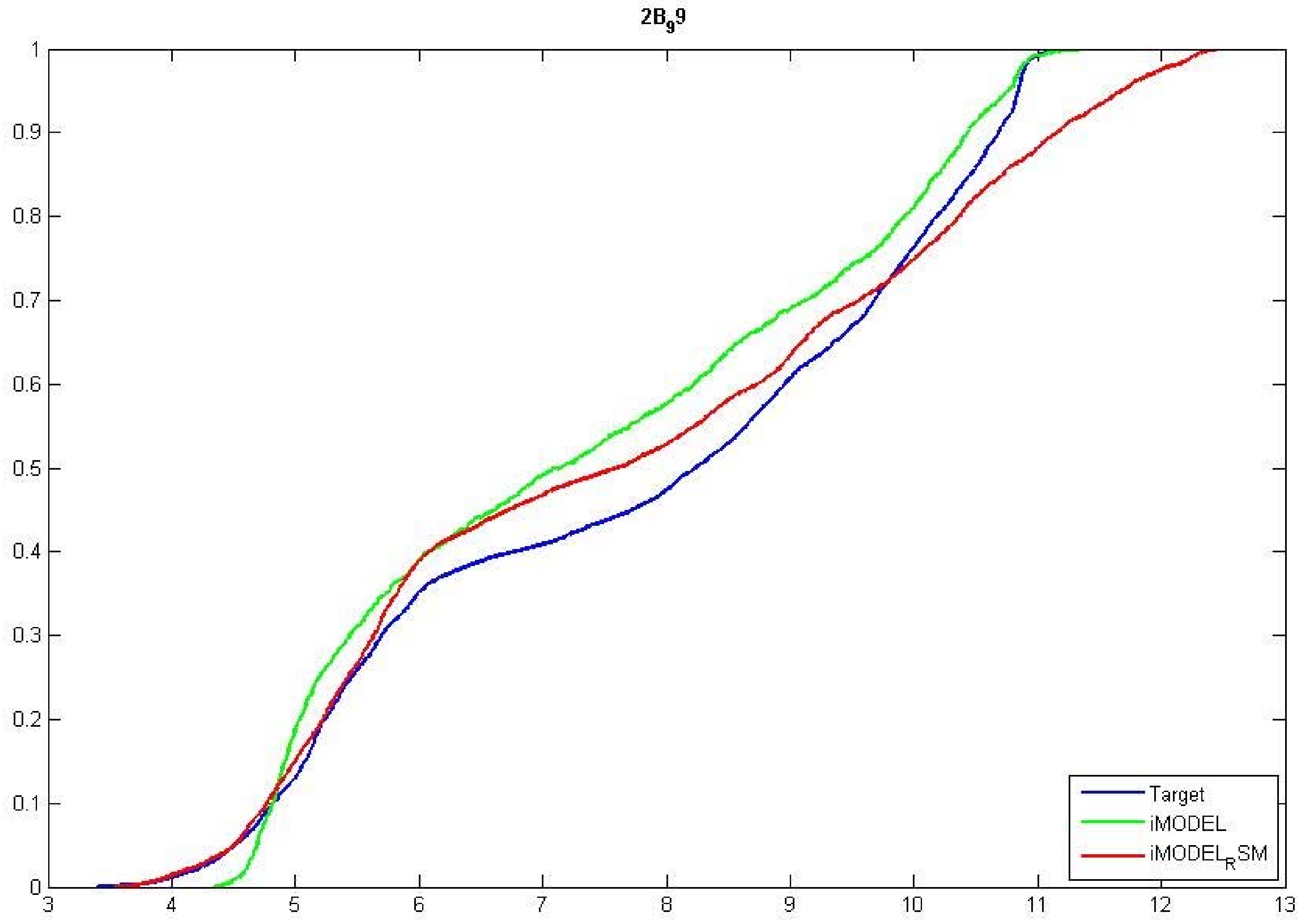

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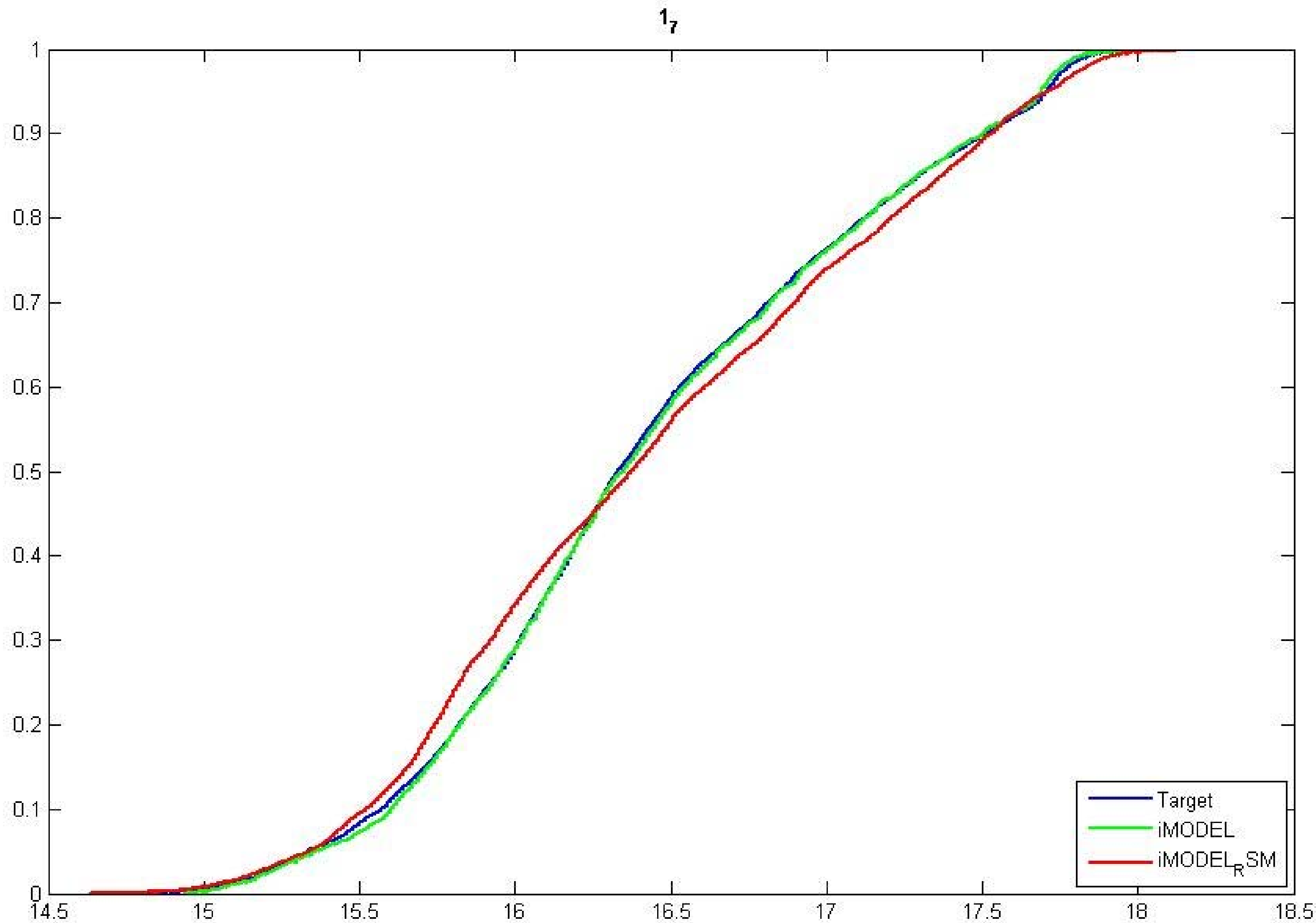

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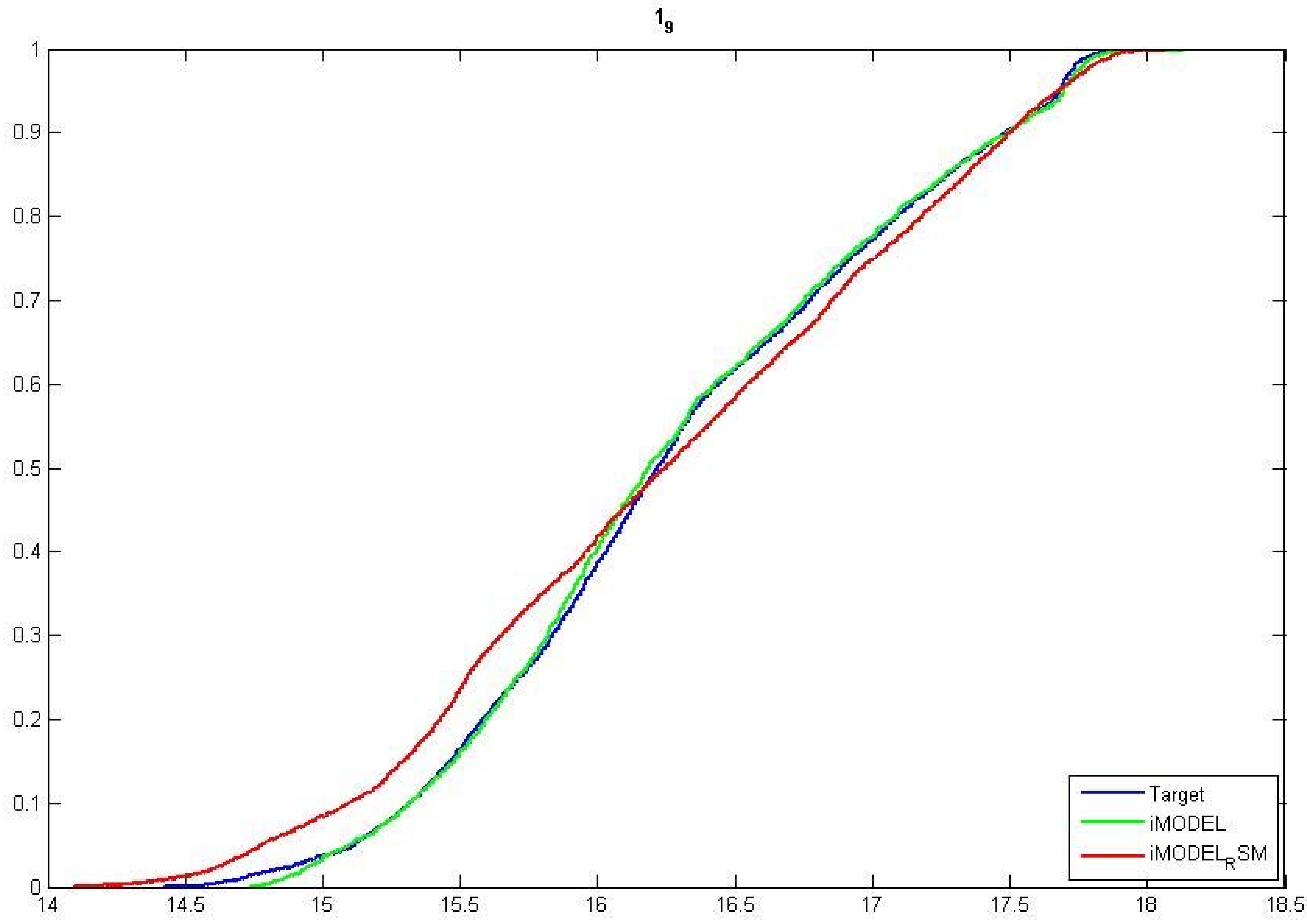
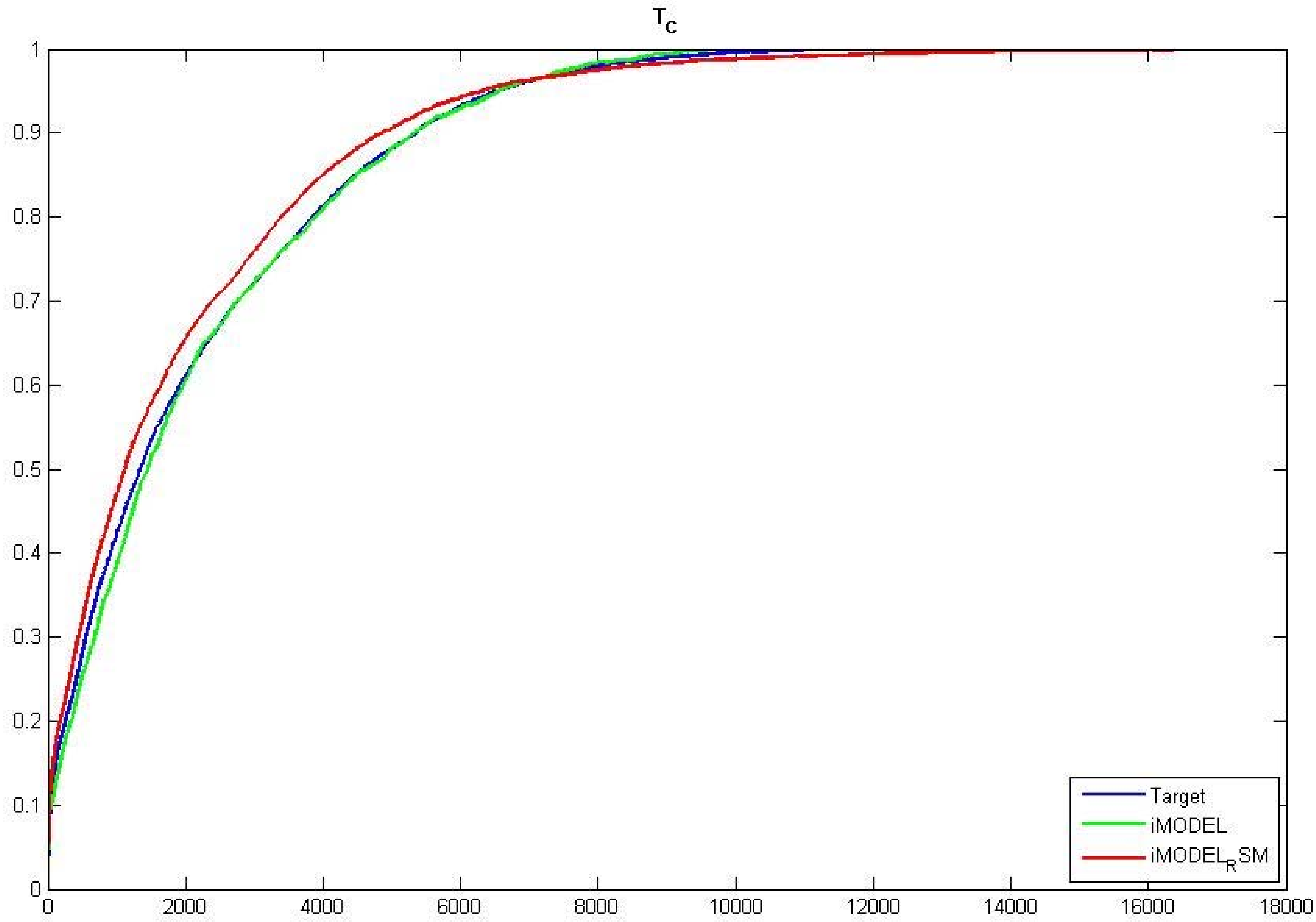


Target, iModel, RSM TC flow duration curve



Application to DECOMP Base Run

- Adversity Trade-Off Matrix
  - *Default weights for all targets is 1 ((13 stage and TC transect flow).*
  - *From the default optimal run, create 14 iMODEL run scenarios (for the 14 targets). For a specific target run scenario, all weights set to unity except the weight of that target set to 2.*
  - *Create ATOM*

Adversity Trade-Off Matrix, ATOM

Default	0.159	0.178	0.360	0.172	0.987	0.127	0.245	0.321	0.169	0.199	0.347	0.422	0.183	0.188	1.852E+06
	3A_NW'	3A_2'	3A_4'	3A_NE'	3_71'	3B_3'	NP_205'	NESRS2'	TC	2A_159'	2_17'	'2B_99'	1_9'	1_7'	MinQnorth
3A_NW'	-36.1%	4.7%	-0.4%	9.1%	1.6%	1.9%	-1.3%	2.6%	1.5%	2.5%	0.7%	0.5%	0.4%	0.7%	-2.9%
3A_2'	3.8%	-17.0%	-4.9%	-8.8%	1.8%	1.9%	1.3%	0.2%	0.0%	1.6%	1.9%	0.0%	1.1%	0.9%	3.3%
3A_4'	-2.5%	-3.0%	-47.5%	-3.4%	6.8%	12.1%	10.7%	15.4%	-0.6%	3.7%	5.1%	4.0%	3.2%	3.3%	3.1%
3A_NE'	12.1%	-5.3%	-4.2%	-22.5%	2.1%	0.0%	2.3%	-1.2%	-0.4%	1.5%	1.7%	-0.3%	1.3%	1.1%	4.8%
3_71'	27.4%	25.4%	52.1%	17.0%	-31.9%	35.1%	33.1%	111.4%	98.9%	4.0%	8.7%	-0.4%	4.5%	5.3%	-1.7%
3B_3'	0.0%	2.2%	2.4%	1.4%	0.5%	-52.9%	31.1%	0.8%	14.5%	2.0%	4.9%	-1.5%	2.0%	2.1%	1.1%
NP_205'	-5.4%	0.4%	-1.3%	2.8%	2.4%	21.4%	-46.4%	2.3%	3.2%	4.3%	1.4%	3.5%	1.1%	0.7%	-0.5%
NESRS2'	4.6%	3.8%	7.3%	1.3%	7.7%	0.2%	0.3%	-53.4%	-13.0%	2.8%	2.7%	0.2%	2.7%	2.9%	-0.1%
TC	0.1%	3.7%	-1.2%	3.7%	2.2%	17.5%	3.1%	-5.6%	-51.5%	2.1%	3.7%	0.3%	5.5%	5.4%	2.1%
2A_159'	3.6%	2.8%	0.8%	2.4%	0.7%	4.6%	4.8%	-0.1%	3.3%	-24.6%	11.2%	55.1%	18.0%	15.5%	0.9%
2_17'	-0.8%	0.2%	0.5%	0.7%	0.2%	2.3%	2.0%	1.7%	4.8%	10.1%	-29.7%	-9.1%	38.3%	32.6%	3.6%
'2B_99'	-0.3%	0.0%	0.0%	-0.4%	0.1%	-0.5%	1.5%	-0.1%	0.0%	3.4%	0.0%	-12.8%	0.9%	1.0%	1.2%
1_9'	0.1%	1.1%	0.7%	0.0%	0.2%	-0.8%	0.9%	0.8%	3.6%	6.0%	9.8%	0.3%	-34.4%	-18.0%	1.2%
1_7'	-0.4%	1.4%	0.6%	0.4%	0.3%	-0.5%	0.8%	0.8%	4.0%	7.3%	11.8%	-0.9%	-14.5%	-27.8%	0.8%
MinQnorth	-7.6%	3.4%	4.2%	6.9%	-0.5%	-1.1%	0.0%	-0.6%	4.4%	1.1%	5.5%	2.0%	20.4%	6.0%	-18.9%

iModel exposure

- Taught at Columbia University, Civil Engineering, Course: CIEN 3250 Hydrosystems Engineering.
- Part of National Science Foundation HydroViz project.
- Key element of the "Growing Blue" award at the American Water Summit 2013
- The Outstanding Project of the Year, ASCE-Palm Beach County Chapter.

iMODEL

FREQUENTLY ASKED QUESTIONS

What is the iModel and how is it different from traditional hydrologic models?

- iModel is an inverse modeling tool that reverses the process of a traditional model
- A traditional model **<u>predicts</u>** a system's **response** (e.g., stage) to the system's ***input*** (e.g., inflows, outflows)
- iModel **<u>computes</u>** a system's ***required input*** (e.g., inflows, outflows) to achieve a system's **desired response** (e.g., stage)
- One iModel run is equivalent to numerous traditional model runs and extensive output analyses.

How is iModel development different from that of traditional hydrologic models?

- Traditional hydrologic models are based on computer's solutions of the laws of physics.
- iModel emulates the reversal of laws of physics using Artificial Neural Networks and Genetic algorithm theories.

What is the significance of iModel?

- Paradigm shift in the modeling culture for the heavily managed Everglades.
- A new perspective of modeling for both planning and real time operations.
- Provides solution to problems traditionally very difficult to address (e.g., operations of the Everglades system with future projects).
- Versatile enough to address water quantity and water quality problems.

How is iModel used?

- Efficient utilization of the available water and the storage facilities to achieve desirable environmental benefits while maintaining flood control and water supply requirements.
- It can guide, and reduce the run time of, traditional models by offering optimal solutions that would otherwise require hundreds of traditional model runs.

How is iModel used?, Cont.

- It provides simple operational functions for complex systems towards Operational Protocols Development.
- A facilitation tool through the Adversity Trade-Off Matrix, ATOM. This matrix is a group of optimal scenarios where each solution emphasizes the gained benefit for an individual competing demand along with the associated gained/lost benefits for the rest of a set of competing demands.

Has iModel been applied to actual projects?

- ***River of Grass Project:*** iModel estimated flow releases throughout the River of Grass Project study area to achieve prescribed stage and flow targets at multiple locations over 36 years under Rainfall Driven Operations.
- ***WCA1 Water Quality Improvement:*** iModel provides more efficient flow releases at S10 structure to improve water quality performance while maintaining the high water performance metric, regulation schedule, and other hydraulic conveyance capacity targets.

Can iModel results be verified using traditional models?

- Yes. Use the iModel's predicted inflows/outflows as input to a traditional model, then check to see if the simulated response of the traditional model matches the desired response of the iModel.
- ***Desired response*** (e.g., stage) → iModel → (***inflows/outflows***) → traditional Model → ***simulated response*** (e.g., stage)