A Historical and Functional Overview of Artificial Intelligence with Hydrology Examples

Emery A. Coppola, Jr., Ph.D.
NOAH LLC, Member of the Tech Parks Arizona

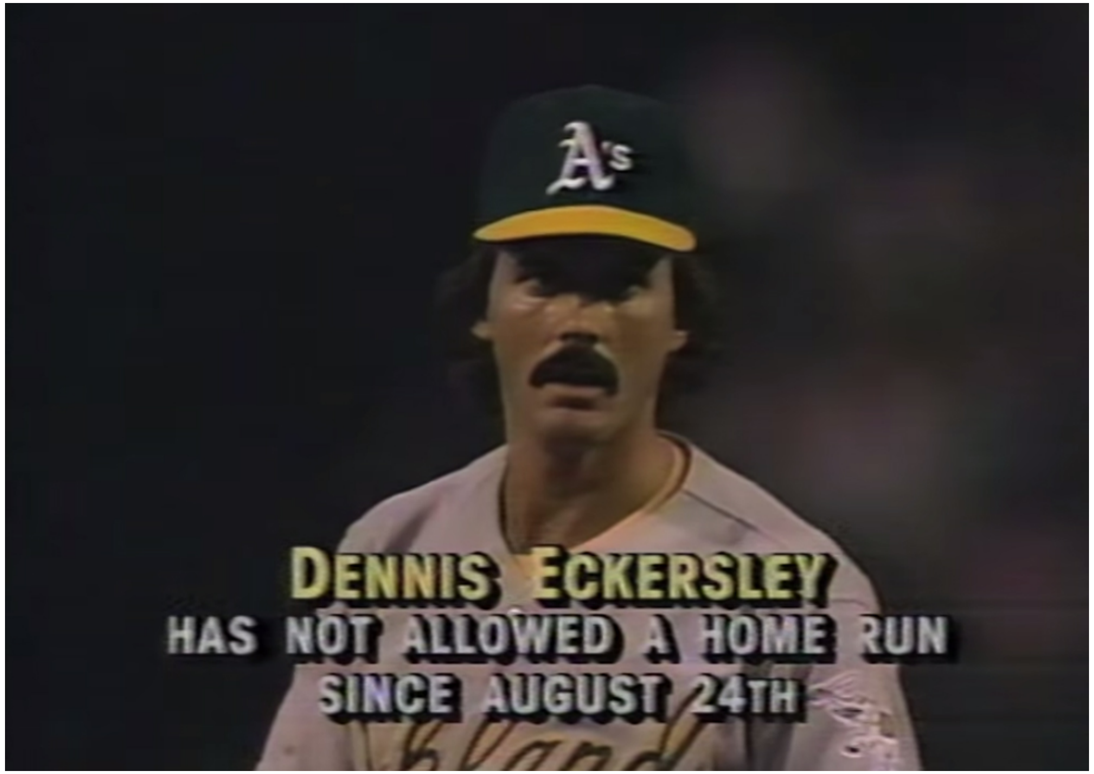
Some Uses of Artificial Neural Networks

- Face recognition
- Speech recognition
- Handwriting recognition
- Autonomous vehicles
- Stock markets
- Targeted marketing
- Inventory analysis

- Fault tracing & diagnosis
- Sensor interpretation
- QC manufacturing
- Process control
- Medical tests
- Chemical analysis
- Baseball Analytics

The Miracle of Perfect Forecasting

Goliath



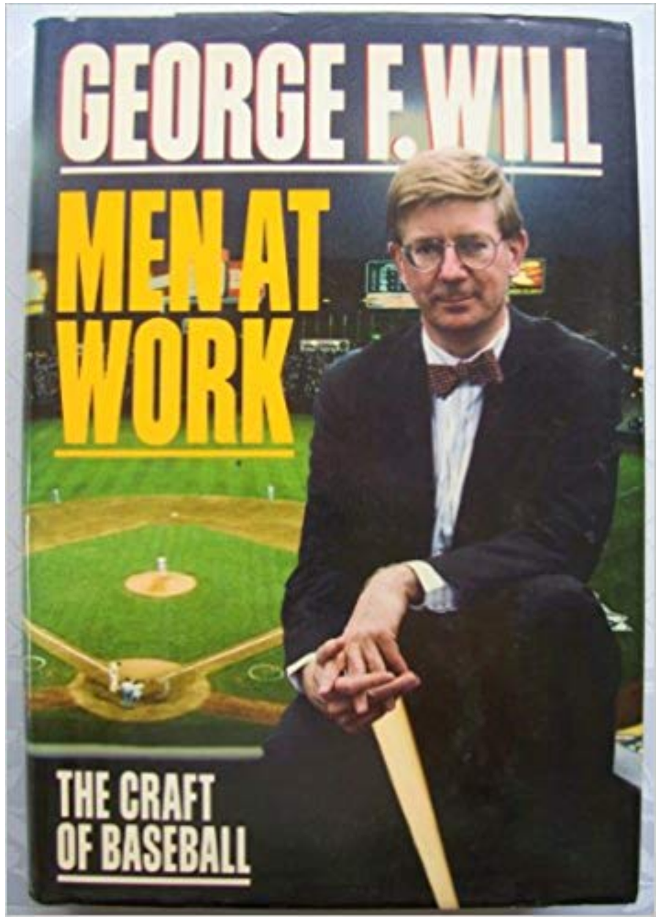
Samson

“I have maybe one good swing in me…”

Game of Numbers

Game of Strategy

When Reason Defies Numbers



What is Artificial Intelligence?

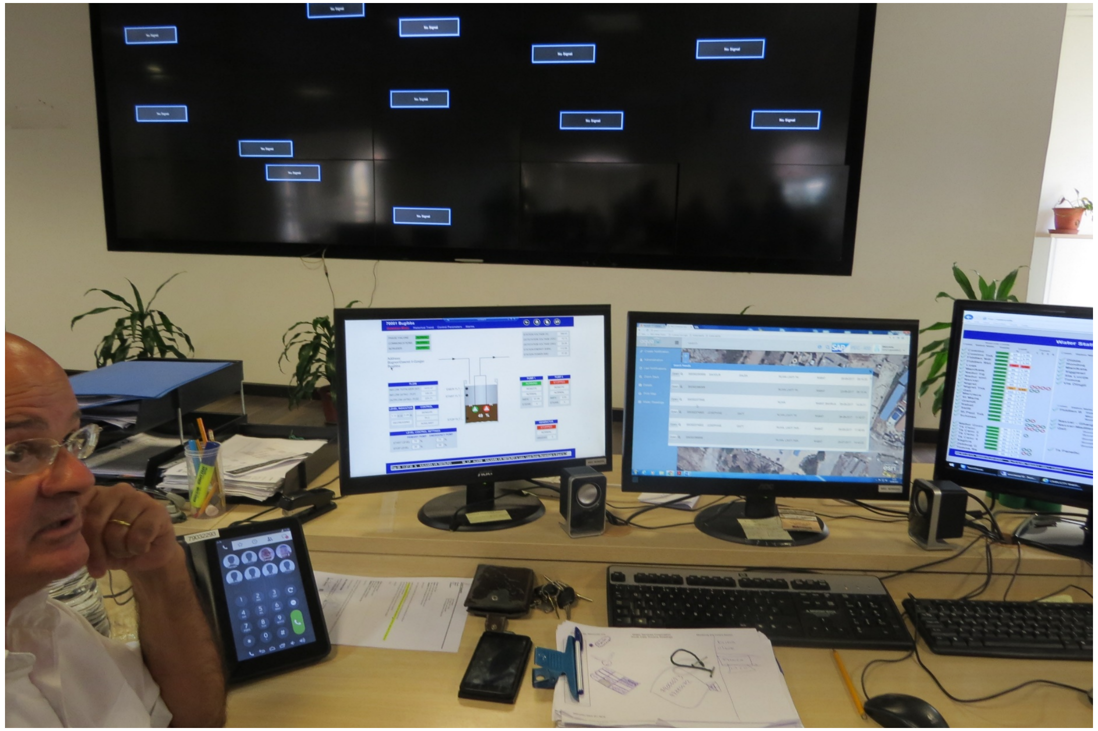
- *The theory and development of computer systems able to perform tasks that normally require human intelligence, such as visual perception, speech recognition, decision-making, and translation between languages.*
- *Many philosophical and intellectual debates on what constitutes "intelligence".*
- *Deep Blue was smart enough to defeat the greatest Chess Master on the planet. However, Deep Blue is not smart enough to want to flee a burning building, or to request another chess match…*

Famous AI Applications

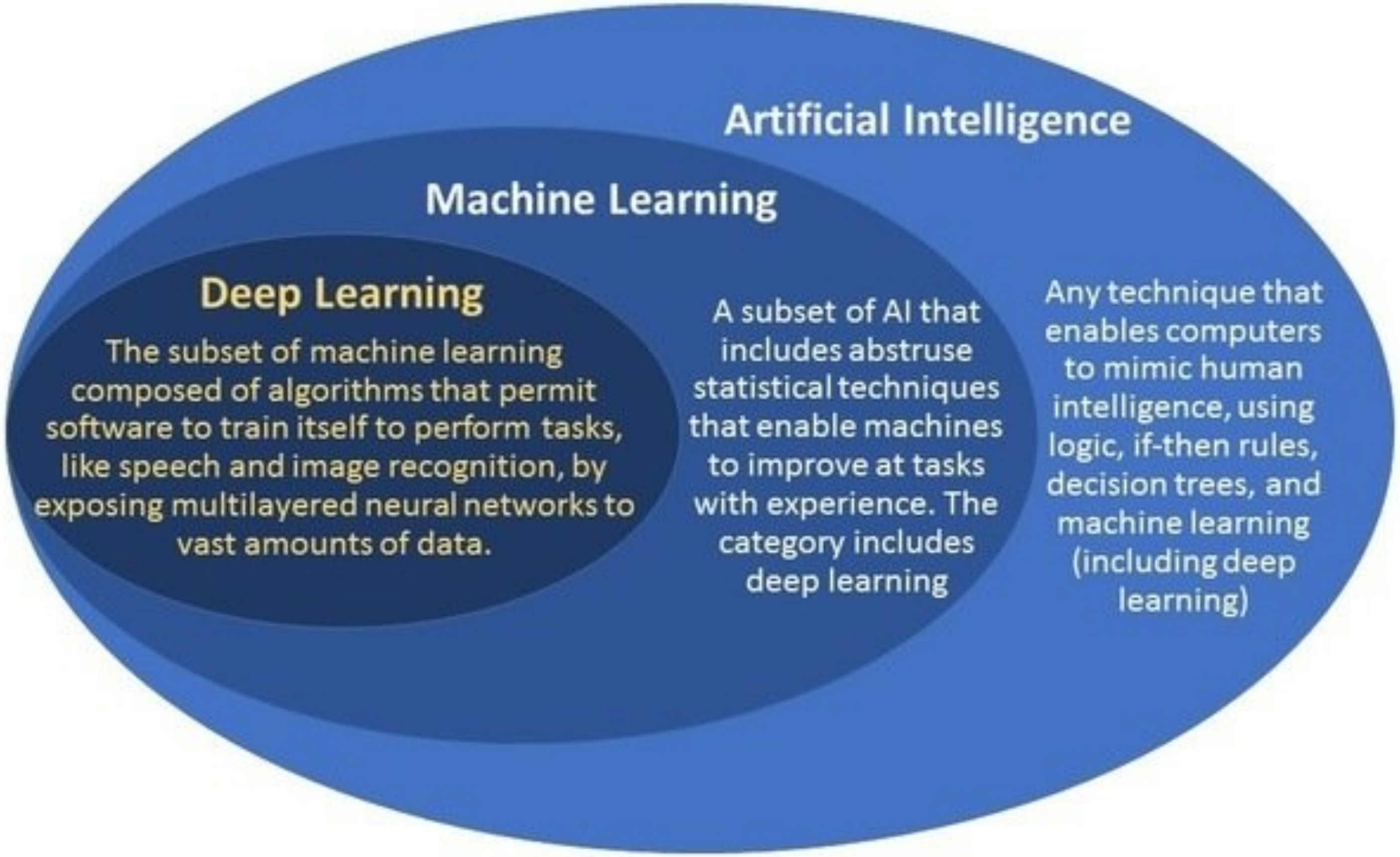
- Alexa’s Speech Recognition
- Waymo’s self-driving cars
- Google’s translations
- Deep Blue trounces Kasparov
- DeepMind’s defeat of world’s top GO player

Example AI Predictions for Water Management

- Surface Water Quality (i.e., algae blooms)
- Groundwater Quality (i.e., saltwater intrusion)
- Groundwater Elevations
- Surface Water Elevations
- Surface Water Flows
- Water Demand
- Water Distribution System Modeling
- Optimizing Groundwater Pumping to Minimize Risk, Maximize Supply, Minimize Costs
- Optimize Water Distribution System Operations



Development of Artificial Intelligence and Deep Learning with Artificial Neural Networks



Early Premonition of AI

- Mary Shelly in her 1818 classic horror story **Frankenstein** not only tapped a nerve in her times regarding artificially created beings, but gave early premonition to fears present today.

Present Day Fear of AI

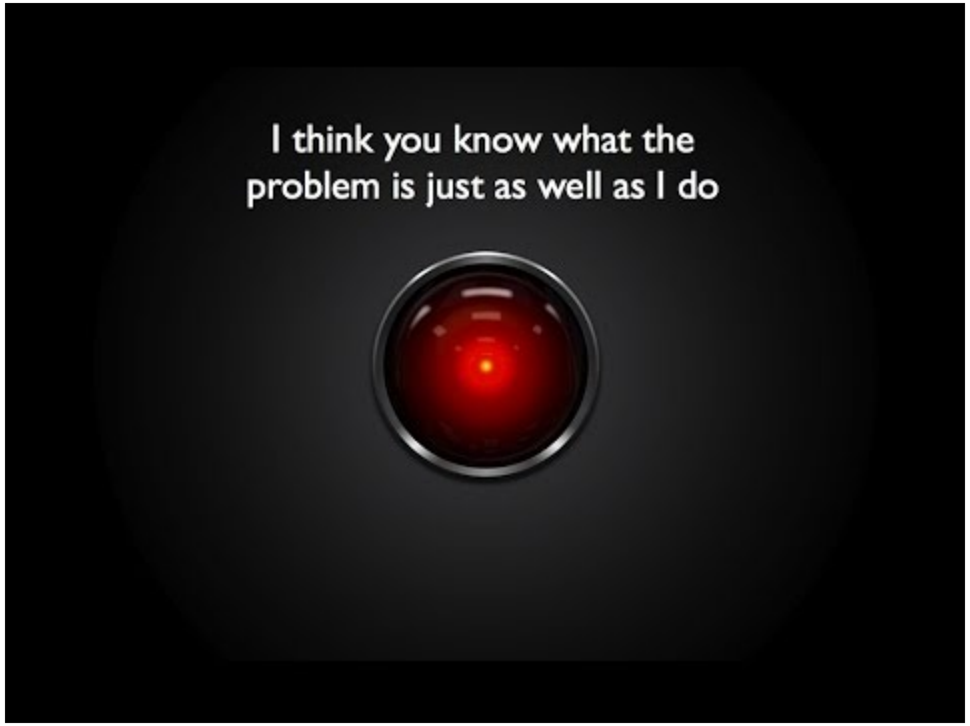
- Eminent physicist Stephen Hawkings considered it perhaps the greatest threat to humanity:
- *“The development of full artificial intelligence could spell the end of the human race.“*
- Tesla founder and techy billionaire Elon Musk:
- *“If you're not concerned about AI safety, you should be. Vastly more risk than North Korea.”*

- I

Charlie Chaplin in his 1936 movie “Modern Times” presciently foresaw the intrusion into and even the domination of intelligent machines on our lives.

AI Dream versus AI Reality

HAL from 2001 and Space Odyssey



"Thank you for telling me the TRUTH.
Dr. Chandler, will I dream?"

Forrest Gump in the Military

"GUMP! What's your sole purpose in this army!?"
"To do whatever you tell me DRILL SARGENT!"

John McCarthy's Bold Prediction

- **In ten years, computers would be able to create better art than any human beings.**
- **Better than DaVinci, Mozart, Shakespeare…**

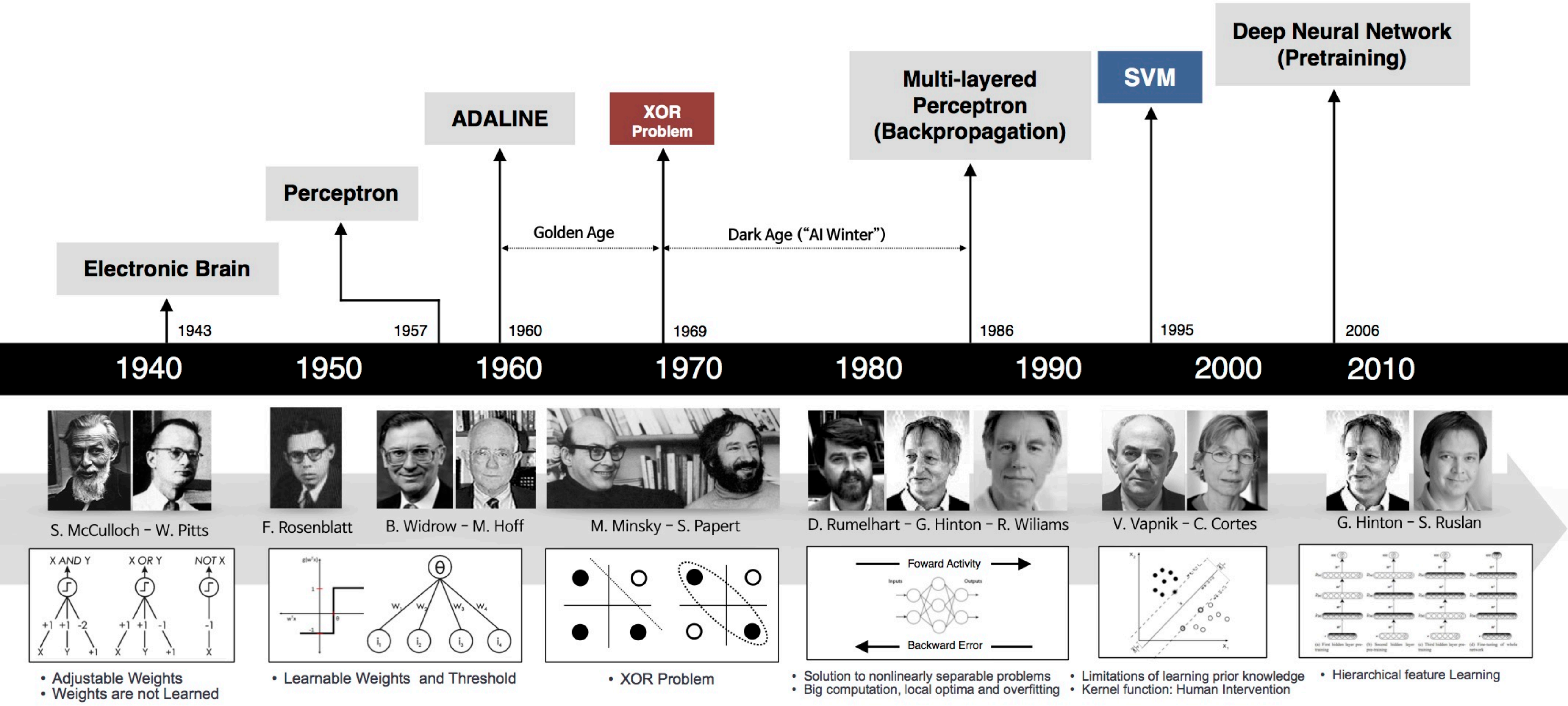
"There are more things in heaven and earth, Horatio, Than are dreamt of in your philosophy." Hamlet.

Father of AI

Alan Turing

Accomplishments

- Famously known for breaking the Nazi’s vaunted secret code Enigma
- The “father” of modern computer programming.
- In 1950, introduced the term “machine learning” and the “Turing Test” for determining equivalence of a computing machine to human intelligence in his landmark paper “*Computing Machinery and Intelligence.”*
- Turing focused on digital machines, not *“clones”.*


Deep Neural Network (Pretraining)
SVM
Multi-layered Perceptron (Backpropagation)
XOR Problem
ADALINE
Perceptron
Electronic Brain
Golden Age
Dark Age ("AI Winter")
1943
1957
1960
1969
1986
1995
2006
1940
1950
1960
1970
1980
1990
2000
2010
S. McCulloch – W. Pitts
F. Rosenblatt
B. Widrow – M. Hoff
M. Minsky – S. Papert
D. Rumelhart – G. Hinton – R. Wiliams
V. Vapnik – C. Cortes
G. Hinton – S. Ruslan
X AND Y
X OR Y
NOT X
Foward Activity
Backward Error
• Adjustable Weights
• Weights are not Learned
• Learnable Weights and Threshold
• XOR Problem
• Solution to nonlinearly separable problems
• Big computation, local optima and overfitting
• Limitations of learning prior knowledge
• Kernel function: Human Intervention
• Hierarchical feature Learning

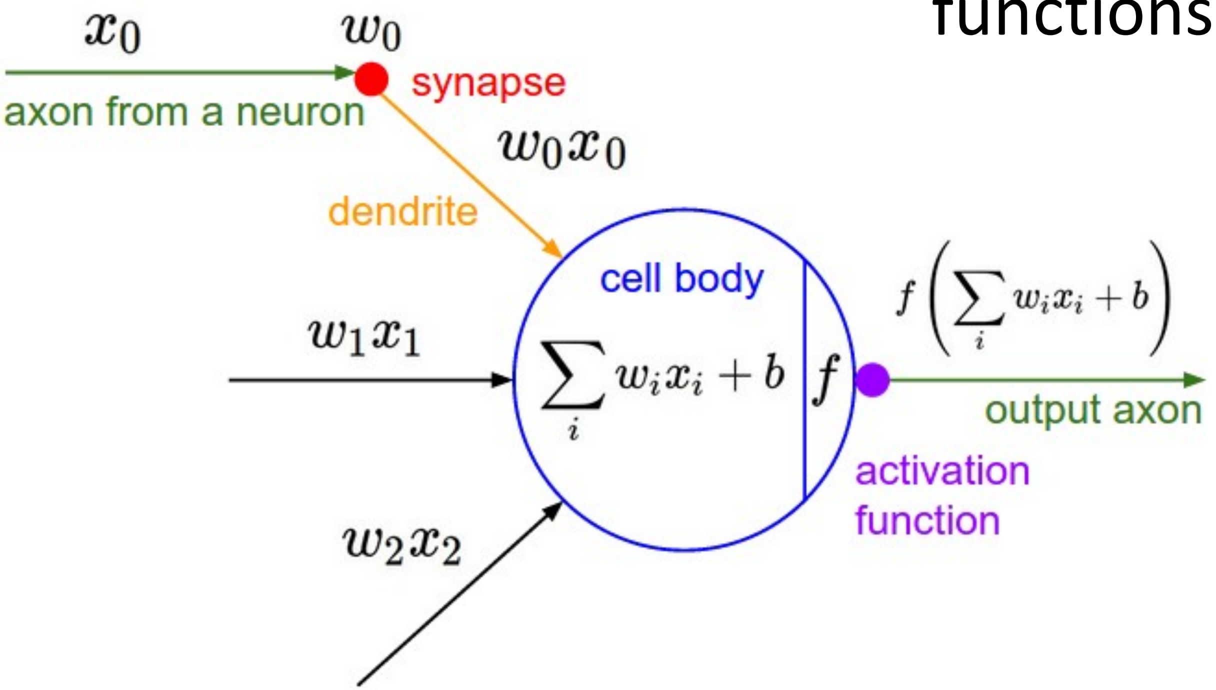
AI Divided into Two Competing Schools

Symbolic Logic View – Expert Systems

"If then" logic with rules to try and replicate the thinking process of humans.

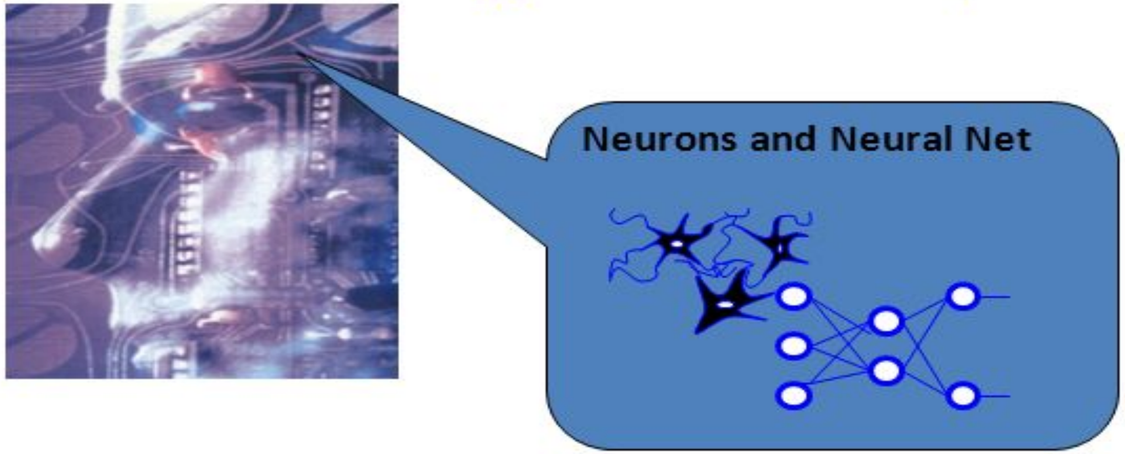
Connectionist View – Artificial Neural Networks

Mimic the brain structure of neurons and synapses via nodes and transfer functions.

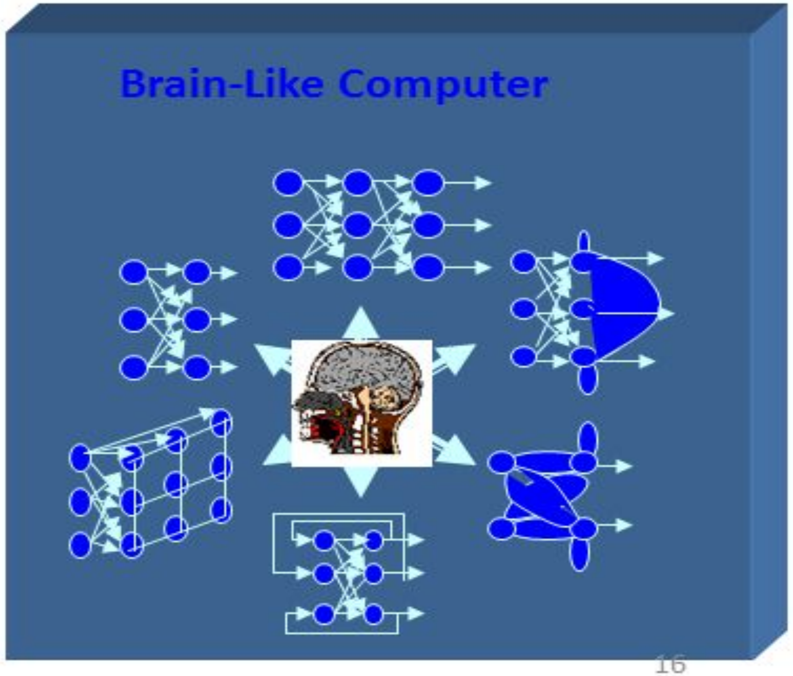


History and Trajectory of Brain-like Computing – Artificial Neural Networks (ANN)

Artificial Neural Network – Mathematical Paradigms of Brain-Like Computer



The new paradigm of computing mathematics consists of the combination of such artificial neurons into some artificial neuron net.



Brain-like computer –

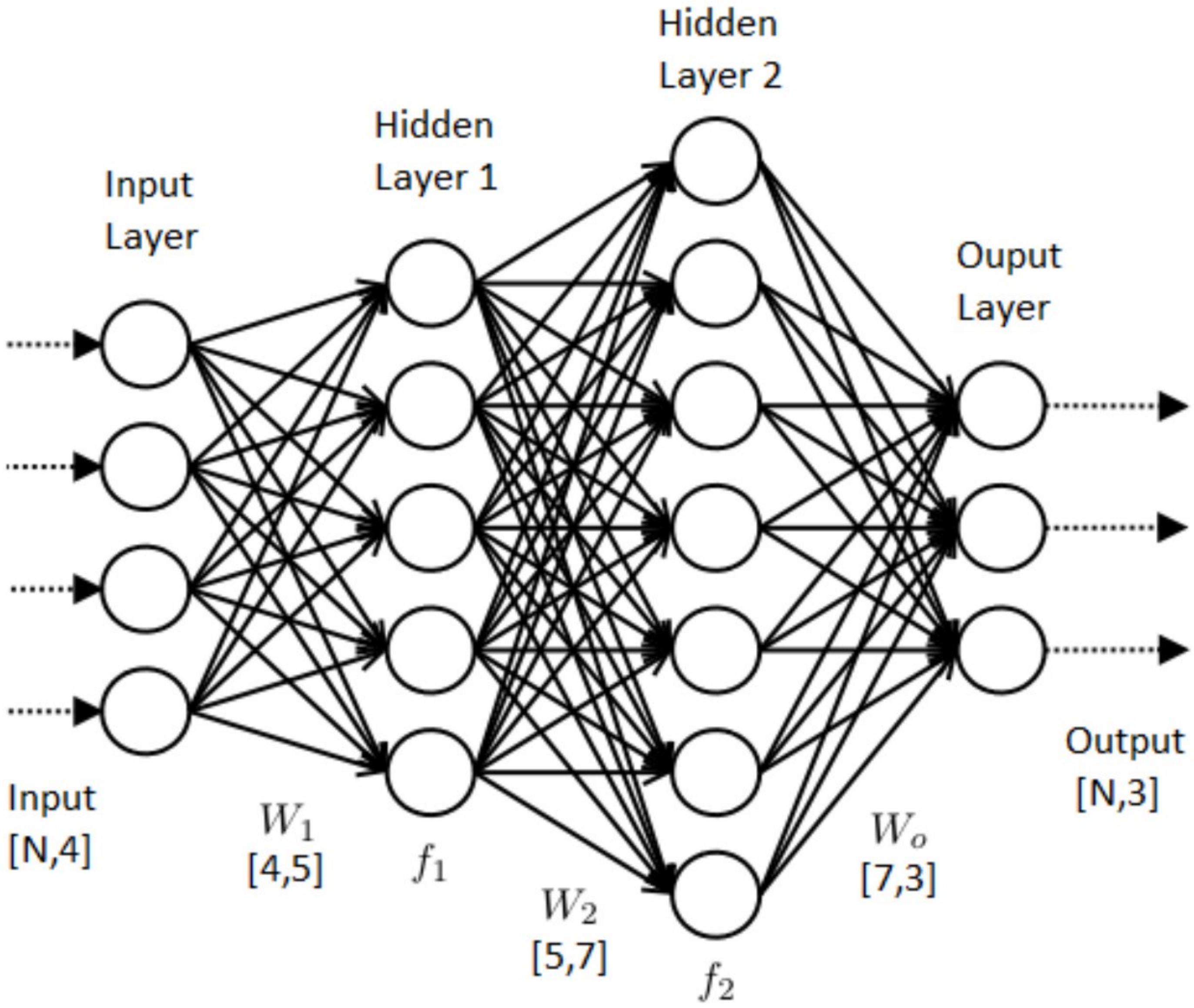
is a mathematical model of humane-brain principles of computations. This computer consists of those elements which can be called the biological neuron prototypes, which are interconnected by direct links called connections and which cooperate to perform parallel distributed processing (PDP) in order to solve a desired computational task.

AI Winter

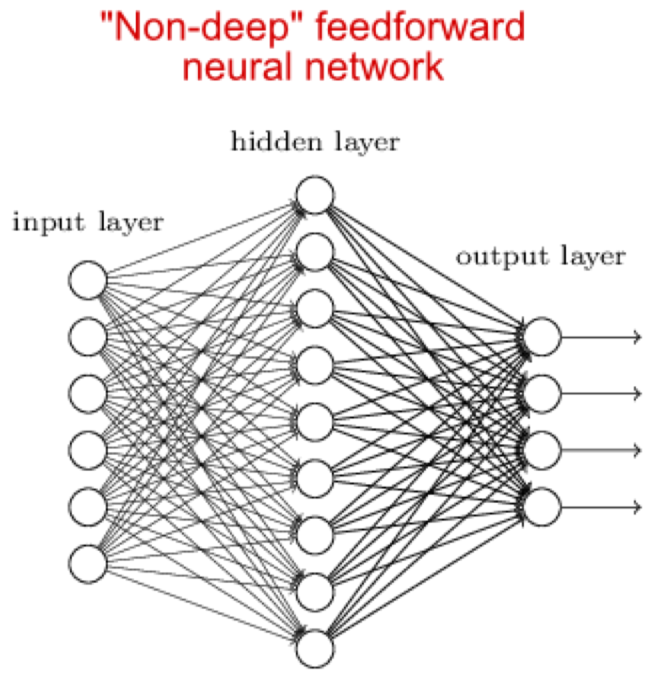
- In their famous/infamous 1969 book *Perceptrons*, Marvin Minsky and Seymour Papert presented mathematical proofs that the current single-layered artificial neural networks could not solve non-linear problems.
- AI government funding dried up almost overnight.

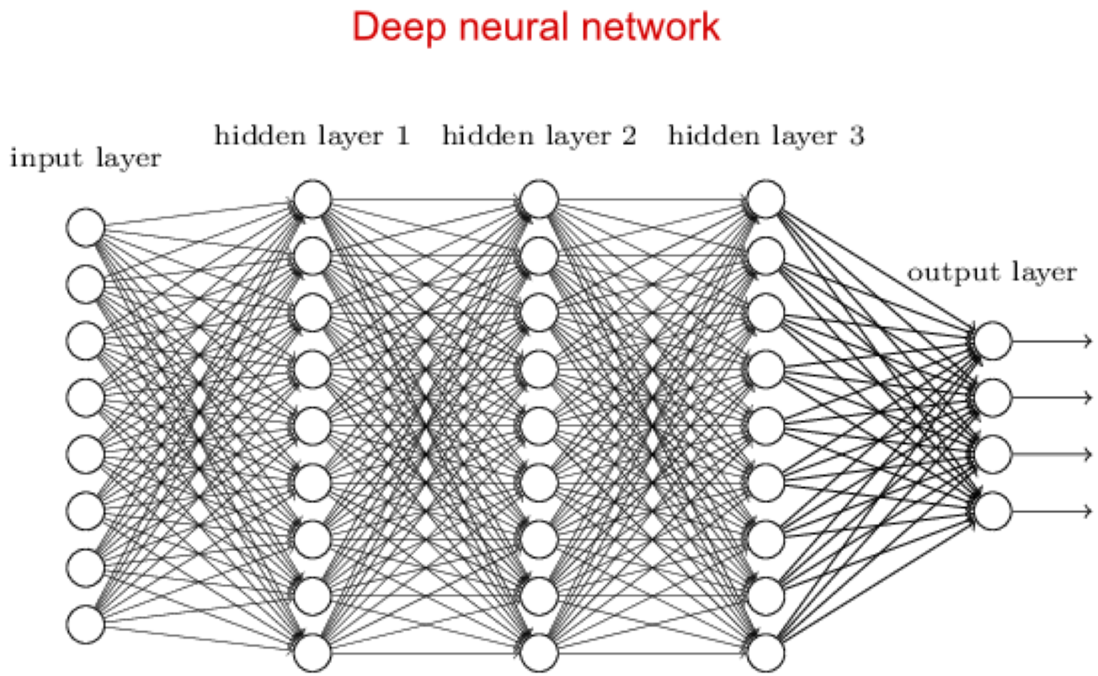
Artificial Neural Network Resurgence

- The Backpropagation Algorithm solved mathematical objections by enabling training of neural networks with one or two hidden layers.
- “Deep Learning” which uses the same neural network structure and algorithms, but with more hidden layers, increases complex modeling capability.
- Enormous data sets and more powerful computing capability ushered in this era.


Hidden
Layer 2
Hidden
Layer 1
Input
Layer
Ouput
Layer
Input
[N,4]
W_1
[4,5]
f_1
W_2
[5,7]
f_2
W_o
[7,3]
Output
[N,3]

Renaissance of Artificial Neural Networks





What Supercharged AI & Deep Learning?

- **Large high quality data sets.**
- **Massive computer power.**
- **Software platforms.**
- **Robust optimizers.**
- **Acceptance in many disciplines and public awareness/acceptance.**

Source: Andrew L Beam
https://beamandrew.github.io/deeplearning/2017/02/23/deep_learning_101_part1.html

Like dogs – ANNs excel at tasks for which they are PROPERLY developed/trained

Still, like a dog, we must be careful how we train the ANN

(a) Husky classified as wolf (b) Explanation

Figure 11: Raw data and explanation of a bad model's prediction in the "Husky vs Wolf" task.

	Before	After
Trusted the bad model	10 out of 27	3 out of 27
Snow as a potential feature	12 out of 27	25 out of 27

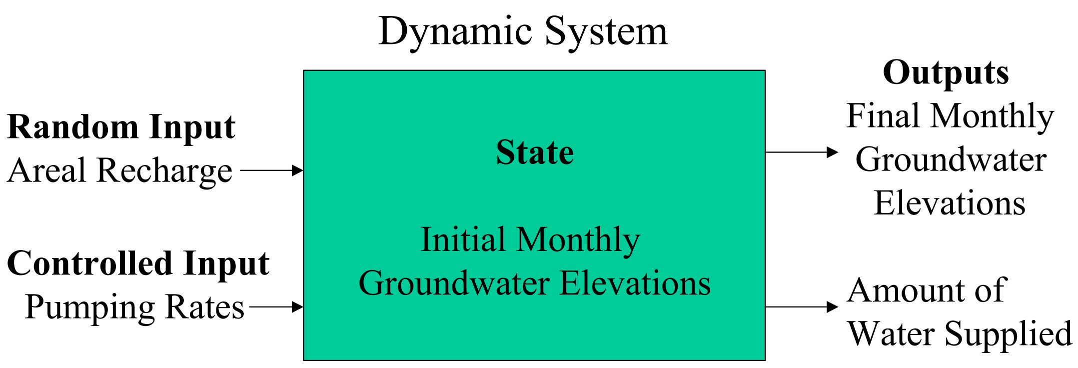
Table 2: "Husky vs Wolf" experiment results.

Questions before Embarking on AI

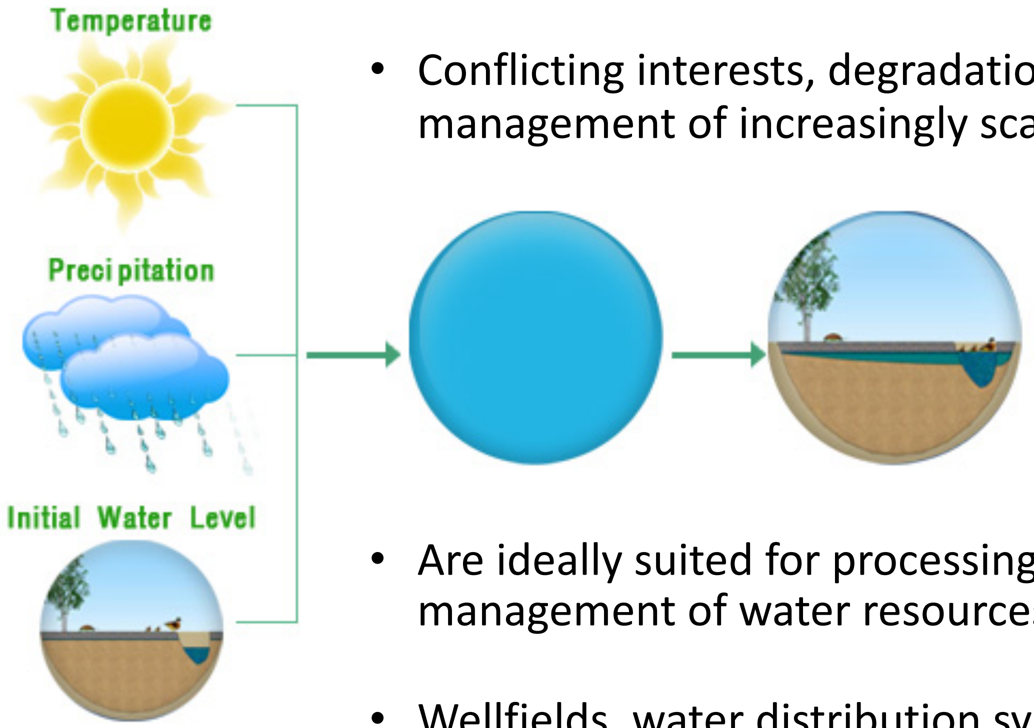
- What are your modeling goals?
- Are they realistic?
  - Problem tractable?
  - Do you understand the governing dynamics/how to model?
  - Sufficient data for model development?
  - Sufficient data for model validation?
  - Can the model be implemented?
  - Will decision makers/potential users/consumers accept it?

Fundamental Understanding of Governing System Dynamics

- General physics
- Important variables
- Spatial factors
- Temporal factors
- Data availability
- Surrogate variables



Artificial Neural Networks in Water Resources



- Data collection and control systems (e.g. SCADA) are becoming extremely common.
  - Real-time collection of climate conditions, system state variables (e.g. water levels, water quality, etc.), and control variables (e.g. pumping rates).
- Conflicting interests, degradation, and diminishment requires improved management of increasingly scarce water resources.
- Are ideally suited for processing data streams for real-time modeling and management of water resources.
- Wellfields, water distribution systems, watersheds, reservoirs, remediation systems, etc., can be instrumented and managed in real time using ANNs.

On the Inherent Difficulty of Modeling Fluid Flow Problems

The Physics of Baseball, 3rd Edition, Harper-Collins Publishers

Author: Dr. Robert Adair, Sterling Professor Emeritus Yale University

"There are two unsolved problems that interest me. The first is the unified theory [which describes the basic structure and formation of the universe]; the second is why does a baseball curve? I believe that in my lifetime, we may solve the first, but I despair of the second."

Quote attributed to unnamed prominent physicist.

THAT AIN'T NO OPTICAL ILLUSION, HE WARNS

First Proof of Concept in Groundwater

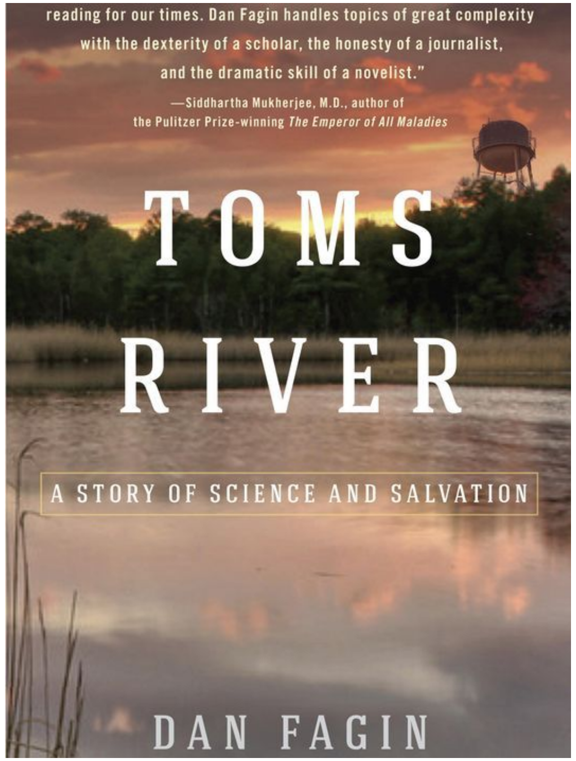
Toms River, New Jersey Wellfield

- Develop ANN models as surrogate of much larger numerical flow model.
- ANN equations predict groundwater level responses to pumping and weather stresses at locations of interest.

ANN-Optimization Approach

- Reduces the number of physical equations by orders of magnitude (from almost 80,000 to less than 50).
- Conducting simulations of different scenarios is orders of magnitude faster with ANN approach, and thus can consider many different scenarios.
- Performing formal decision-making methodology is much more efficient and is less susceptible to identification of erroneous/infeasible solutions.
- ANN serves as a “meta-model” for the much more mathematically dense and difficult to solve numerical model.
- A more accurate predictor model will result in more accurate optimization solutions.

AI Prediction and Multi-Objective Optimization

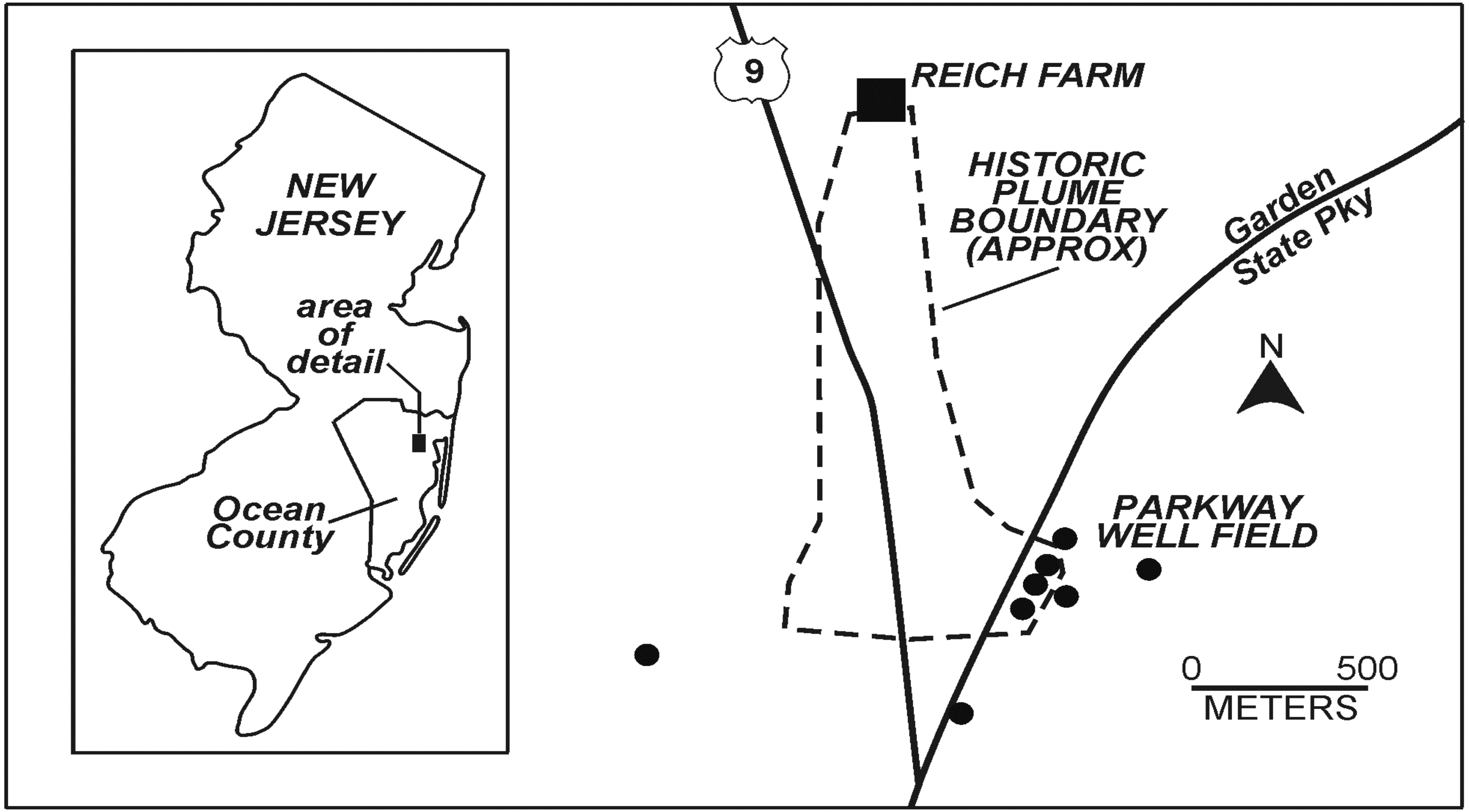


Paper Published, Journal of Ground Water, 45, no 1: 53-61, 2007, Coppola and others, Multiobjective Analysis of a Public Wellfield Using Artificial Neural Networks.

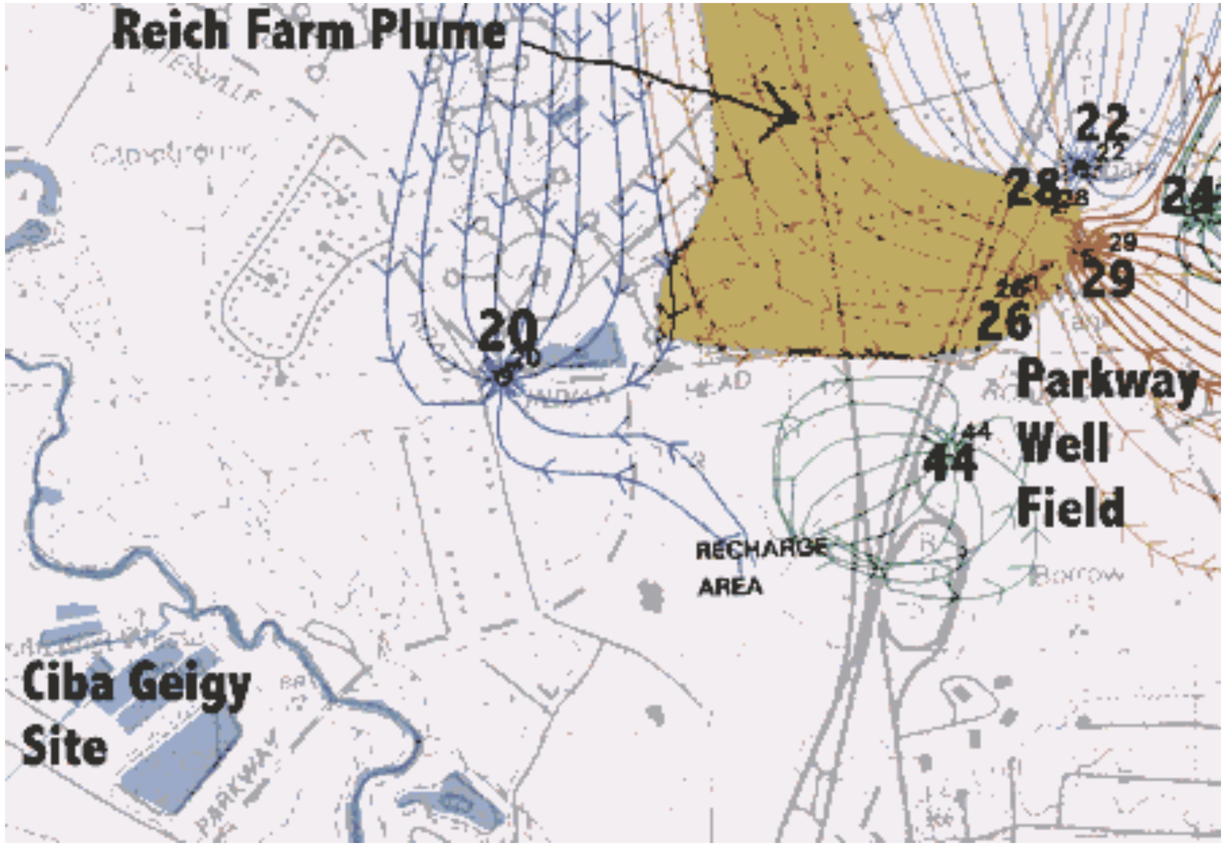
A ten million dollar epidemiological study conducted over six years found a statistically significant correlation between incidence of leukemia in young girls and exposure to contaminated drinking water from municipal supply wells.

Historic carousel on board walk by ocean.

Groundwater Contamination Plume Impacted Water Supply



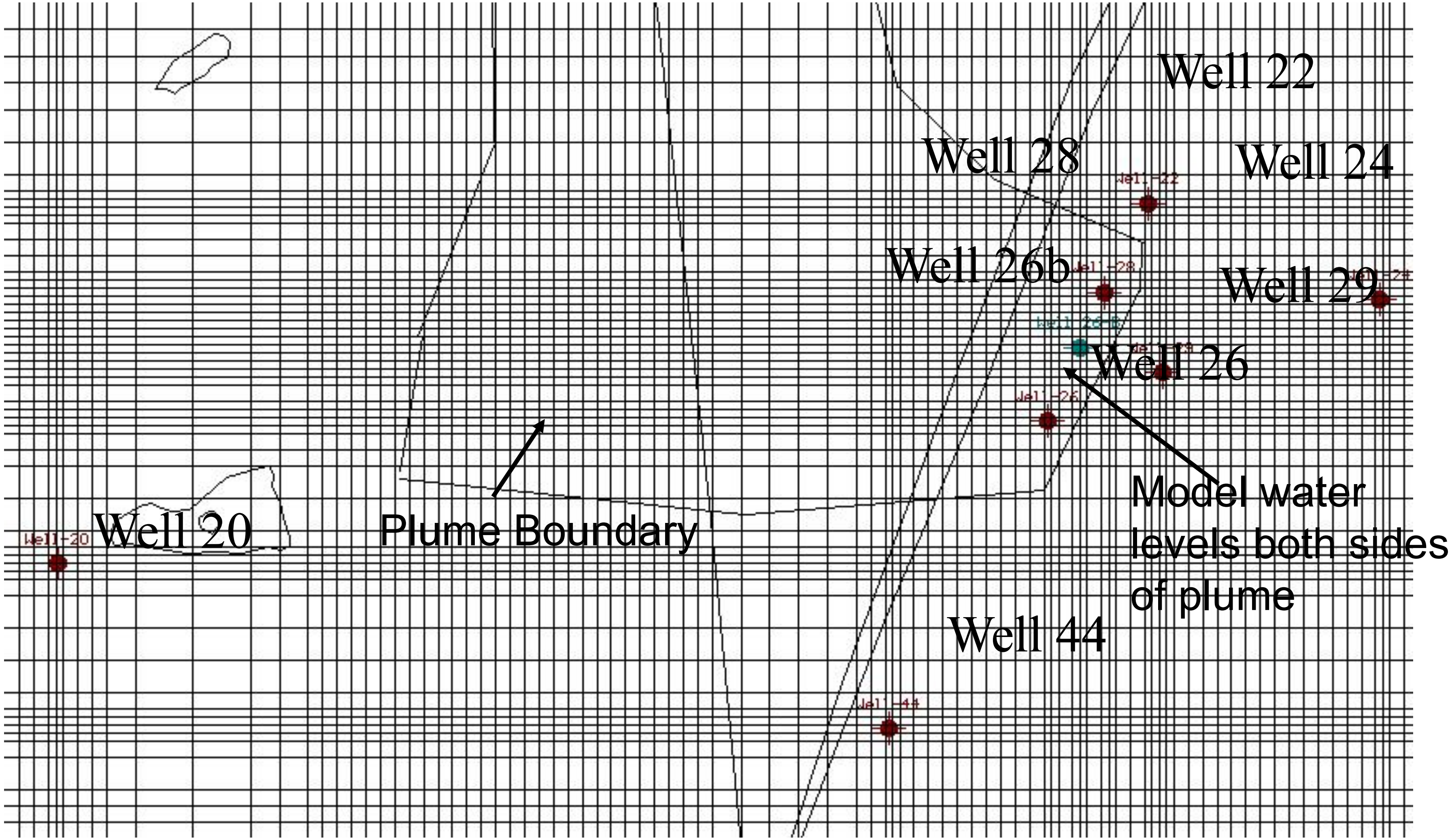
Plume, Wellfield, and Simulated Ground-Water Flow Lines Demonstrating Risk of Wells to Contamination.



Management Problem

- Former supply wells located inside of plume area now used to "capture" contamination and protect nearby clean supply wells.
- However, during high water demand periods, higher pumping of the clean supply wells can "capture" contaminated water, and in fact have shown presence of contamination during these higher risk periods.
- The New Jersey Geological Survey developed a numerical ground-water flow model (MODFLOW) to simulate movement of the groundwater contaminant plume under variable pumping and weather conditions.
- Goal is to find optimal pumping rates of supply wells that balance the conflicting objectives of maximizing water supply while minimizing the risk of contamination.

Model Grid Domain Vicinity of Plume and Wells

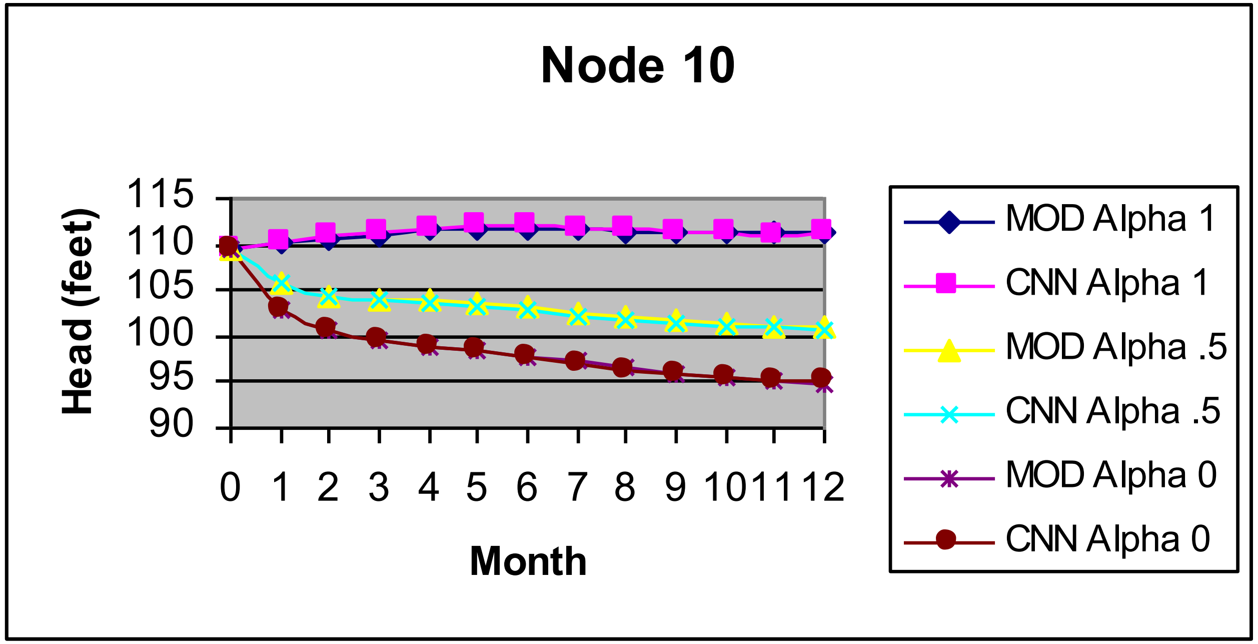


MODFLOW Simulation Data for ANN Model Development

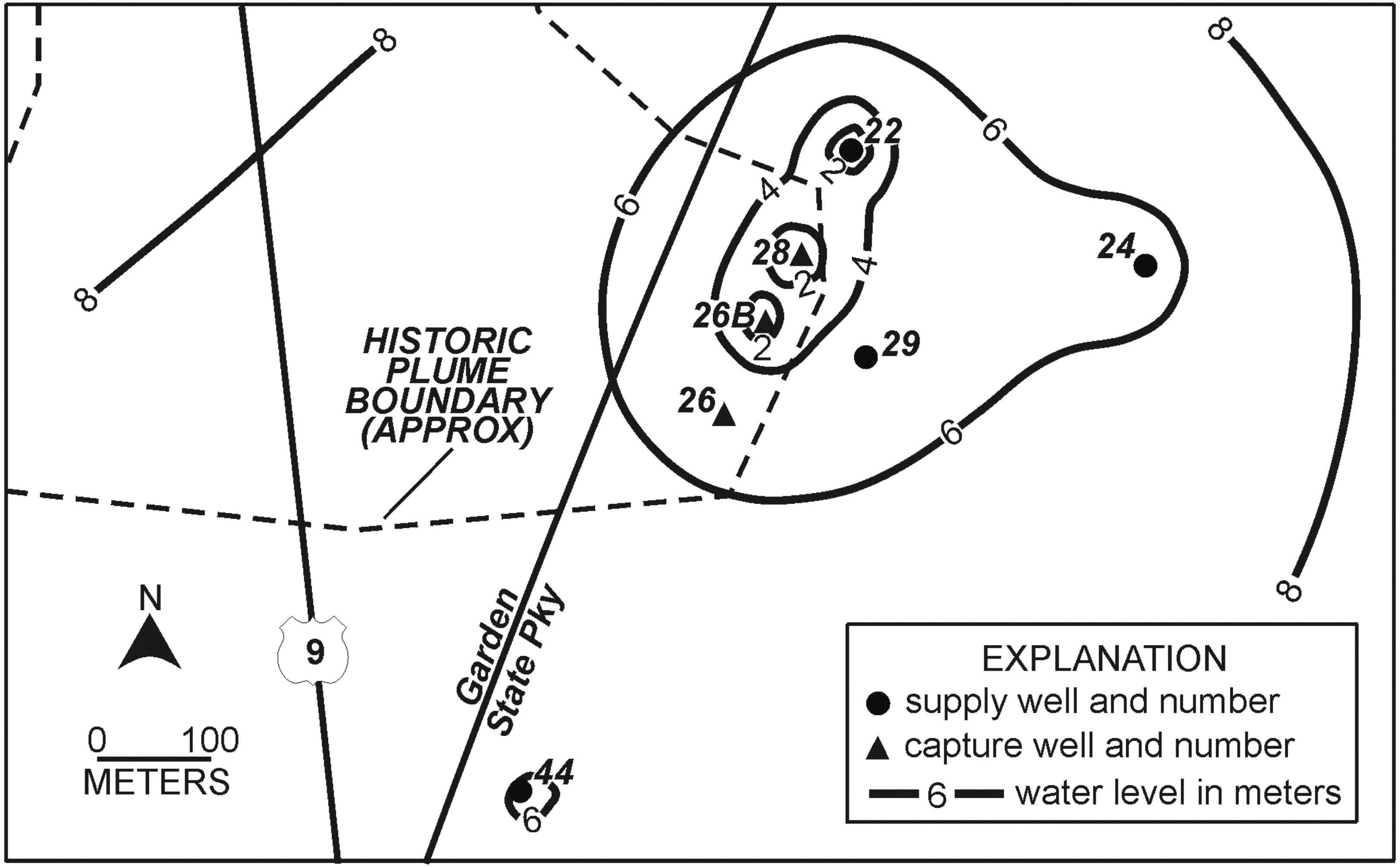
- 5 years of monthly groundwater recharge values
- Randomly generated monthly pumping rates, ranging from 0 to 1,000 gpm, pumping rates are independent.
- MODFLOW run for 30,720 consecutive monthly stress periods using random and controlled inputs. Each month numerically simulated 2,560 times.
- Half (1,280) used for training.
- Developed a single ANN model for each month, and coupled the twelve ANN monthly models together to simulate a complete one year horizon.

Summary of Dynamic Nature of Toms River Groundwater System & Linked ANN Predictive Accuracy

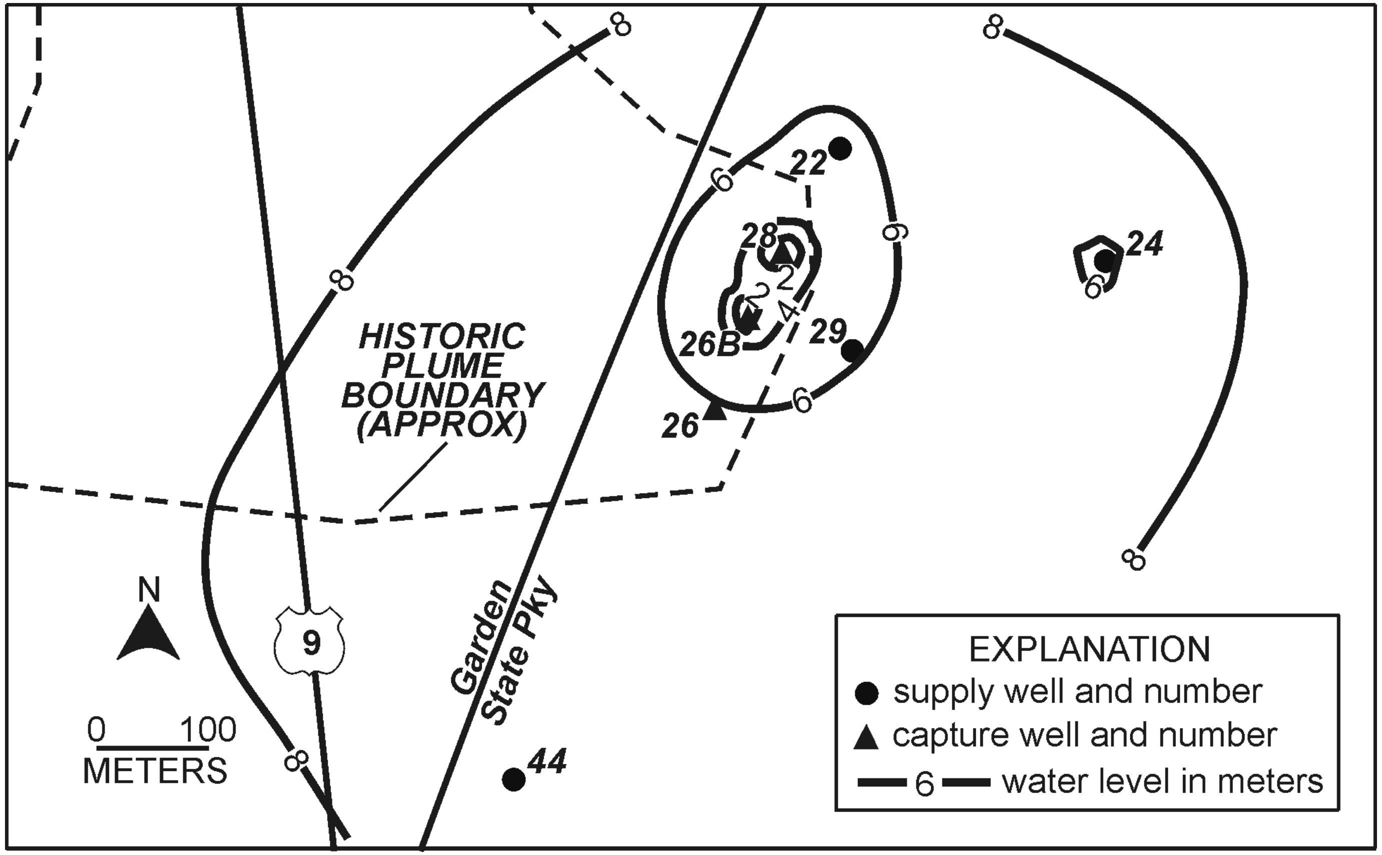
- Groundwater elevations across the model over the various stress periods ranged from approximately -10.0 to 40.0 feet (above mean sea level).
- Mean monthly change in groundwater elevations at all nodes is 2.3 feet.
- Maximum monthly change in a groundwater elevation is 30.6 feet.
- Maximum mean monthly change in groundwater elevations for a single location is 5.7 feet.
- Of the 384 mean head values, 247 estimated by the ANN during validation matched exactly with the MODFLOW values, 136 differed by only 0.1 feet, and the remaining one differed by 0.2 feet.
- The mean absolute error is 0.1 feet.
- The maximum error is 0.98 feet.



Optimal Solution with Water Supply Weight = 0.5 and Risk = 0.5



Optimal Solution with Water Supply Weight = 0.4 and Risk = 0.6



First AI Ground-Water Level Prediction for Real-World System
Tampa Bay, FL

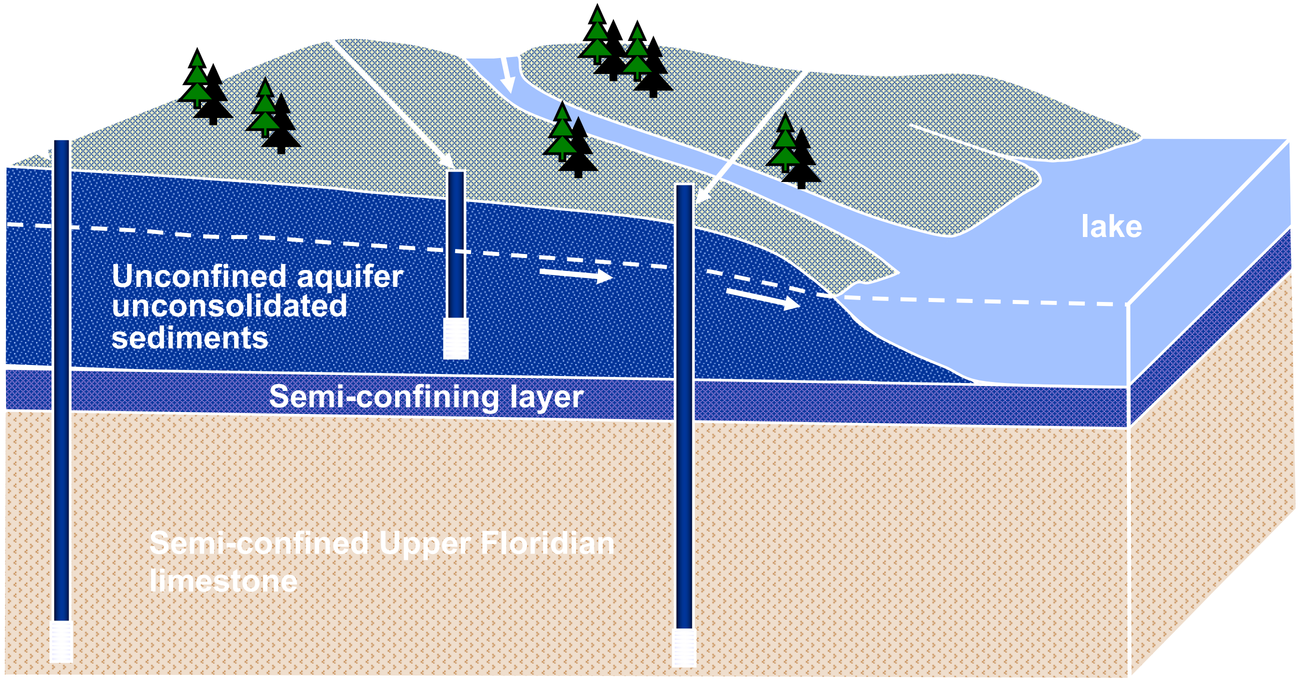
- Over-pumping of the groundwater system has resulted in severe environmental impacts, including streamflow depletions, drying of wetlands and swamps, land subsidence, etc.
- Tampa Bay Water utility must meet groundwater level targets bi-weekly or face regulatory fines.
- Need a more accurate ground-water level prediction model based upon climate and pumping conditions.

📖 ***See highly acclaimed book "Water Follies" Island Press, 2002***

Groundwater Elevation Predictions
Tampa, Florida

- Predicting groundwater elevations in both an unconfined sediment aquifer and a semi-confined limestone aquifer in response to variable pumping and weather conditions.
- Perform sensitivity analysis to identify the relative importance of different input variables on groundwater elevations.

Tampa Bay Hydrogeology



Paper published, Journal of Hydrologic Engineering Volume 8, No. 6, November/December 2003, Coppola and others

Artificial Neural Network Approach for Predicting Transient Water Levels in a Multilayered Groundwater System under Variable State, Pumping, and Climate Conditions

Tampa Bay Water ANN Data

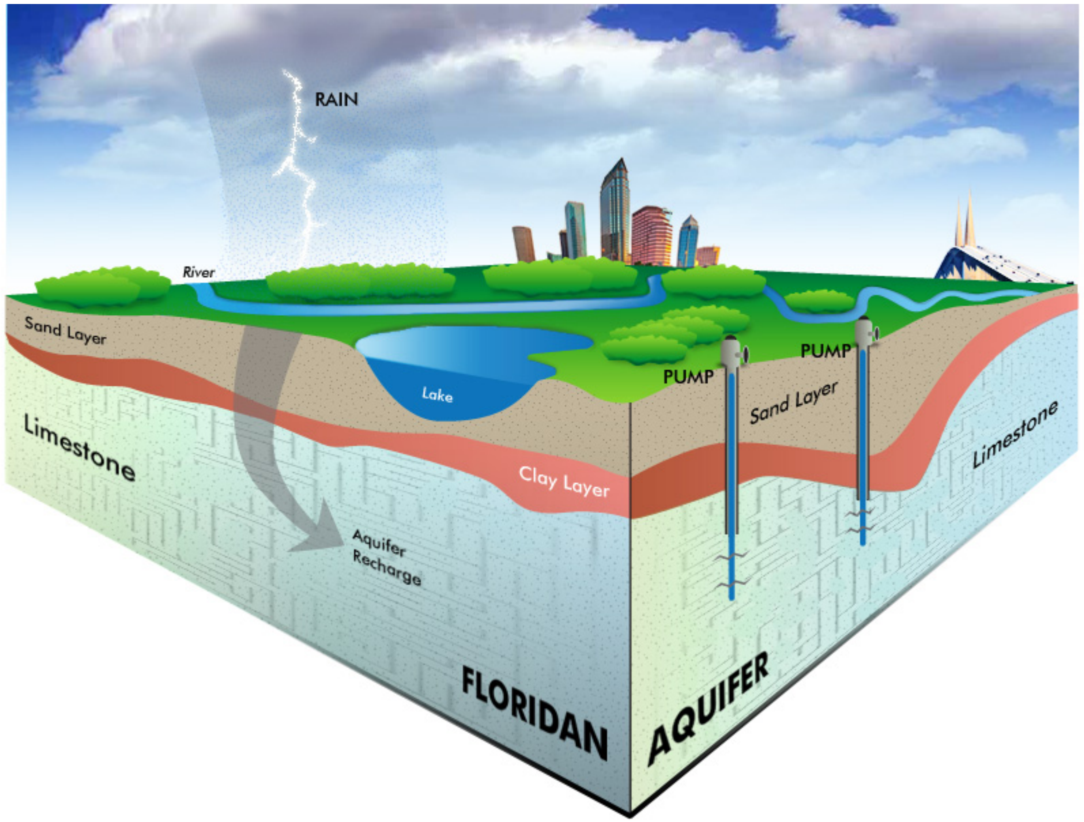
- 5 years of data consisting of ground-water levels, pumping rates, and weather variables, with water levels usually measured **(MANUALLY)** on a weekly frequency.

- Input variables were initial ground-water levels in 12 monitoring wells, pumping extractions of 7 municipal wells, precipitation, temperature, wind speed, dew point, and stress period length.

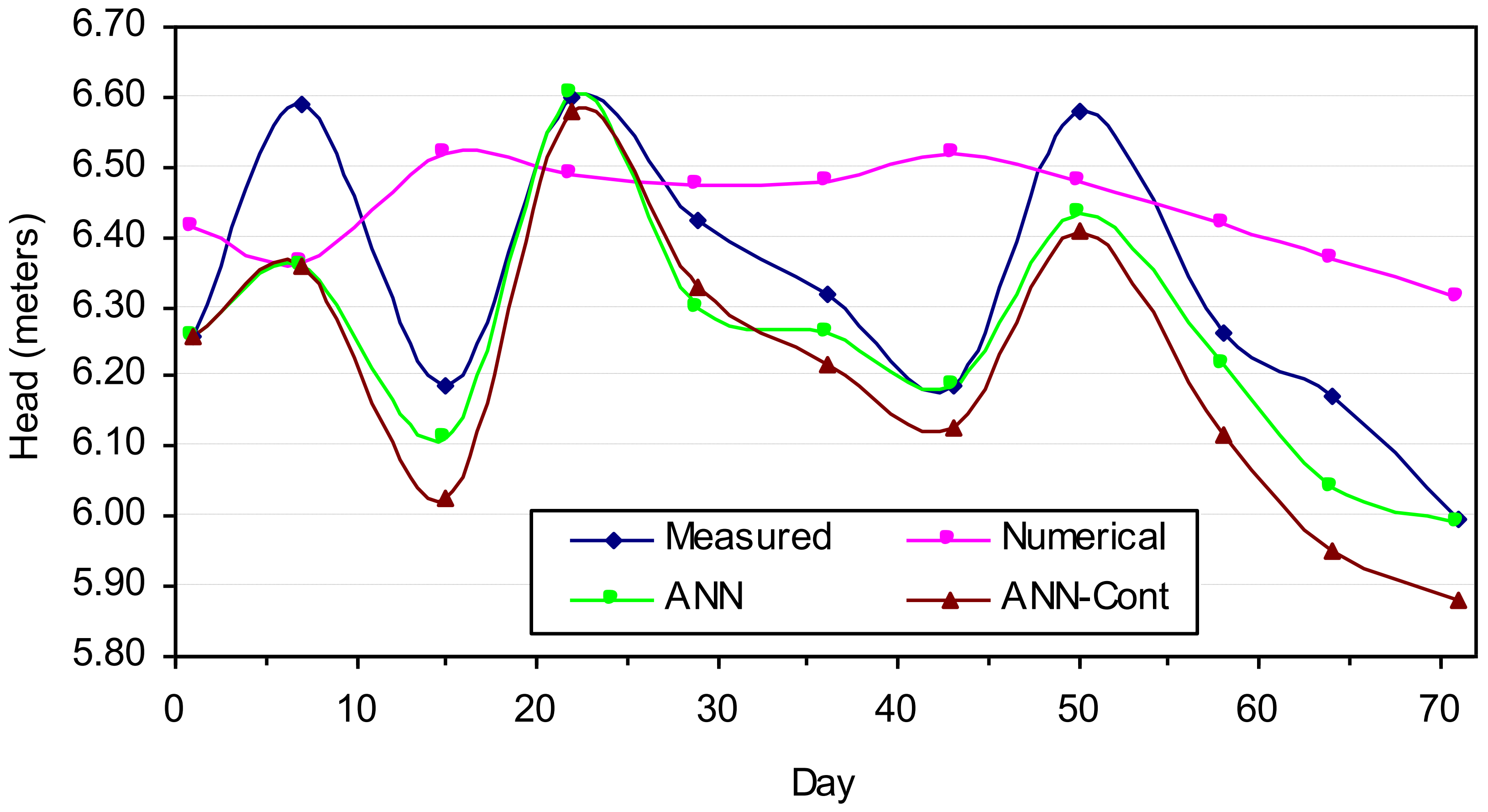
- Output variables were ground-water levels at 12 monitoring wells at the end of each stress period, varying from 3 to 24 days.

Predictive Performance Assessment

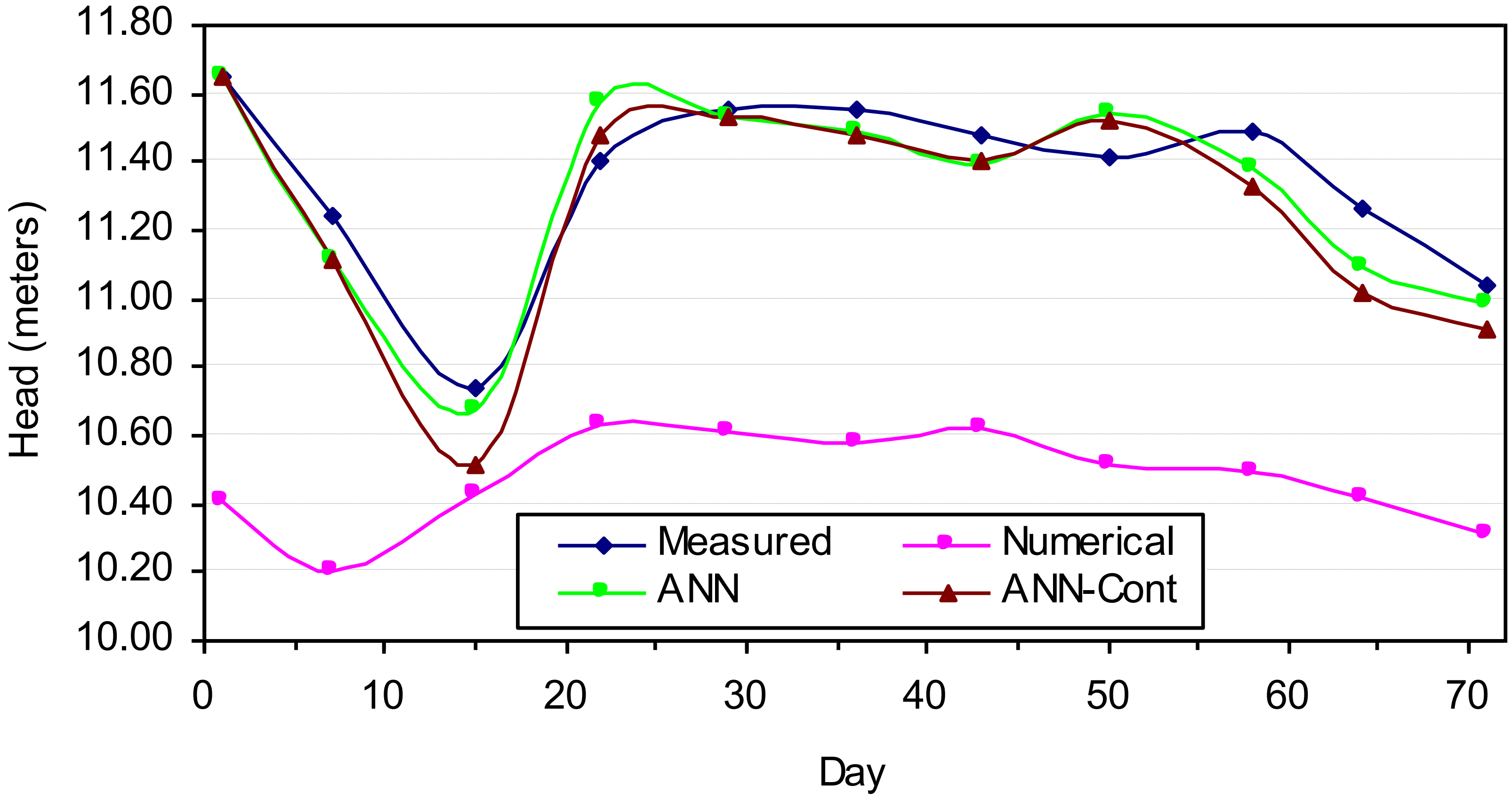
- Compare ANN performance against extensively calibrated numerical groundwater flow model (MODFLOW) developed by utility consultants.
- Compare against measured water levels
- Mean absolute error of ANN over validation period was 0.5 feet.
- Mean absolute error of MODFLOW over same period was 2.5 feet.



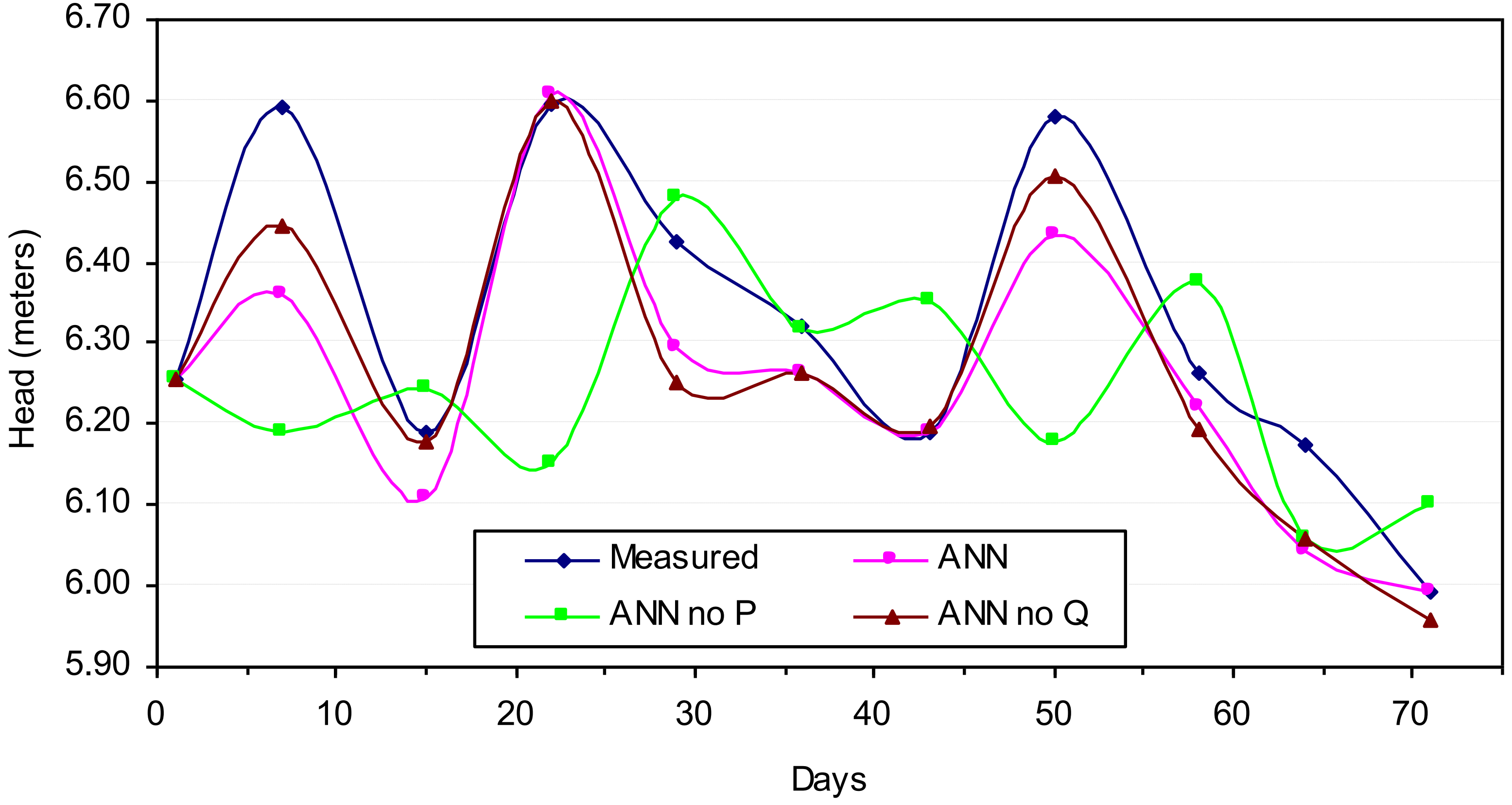
Unconfined Aquifer - Validation



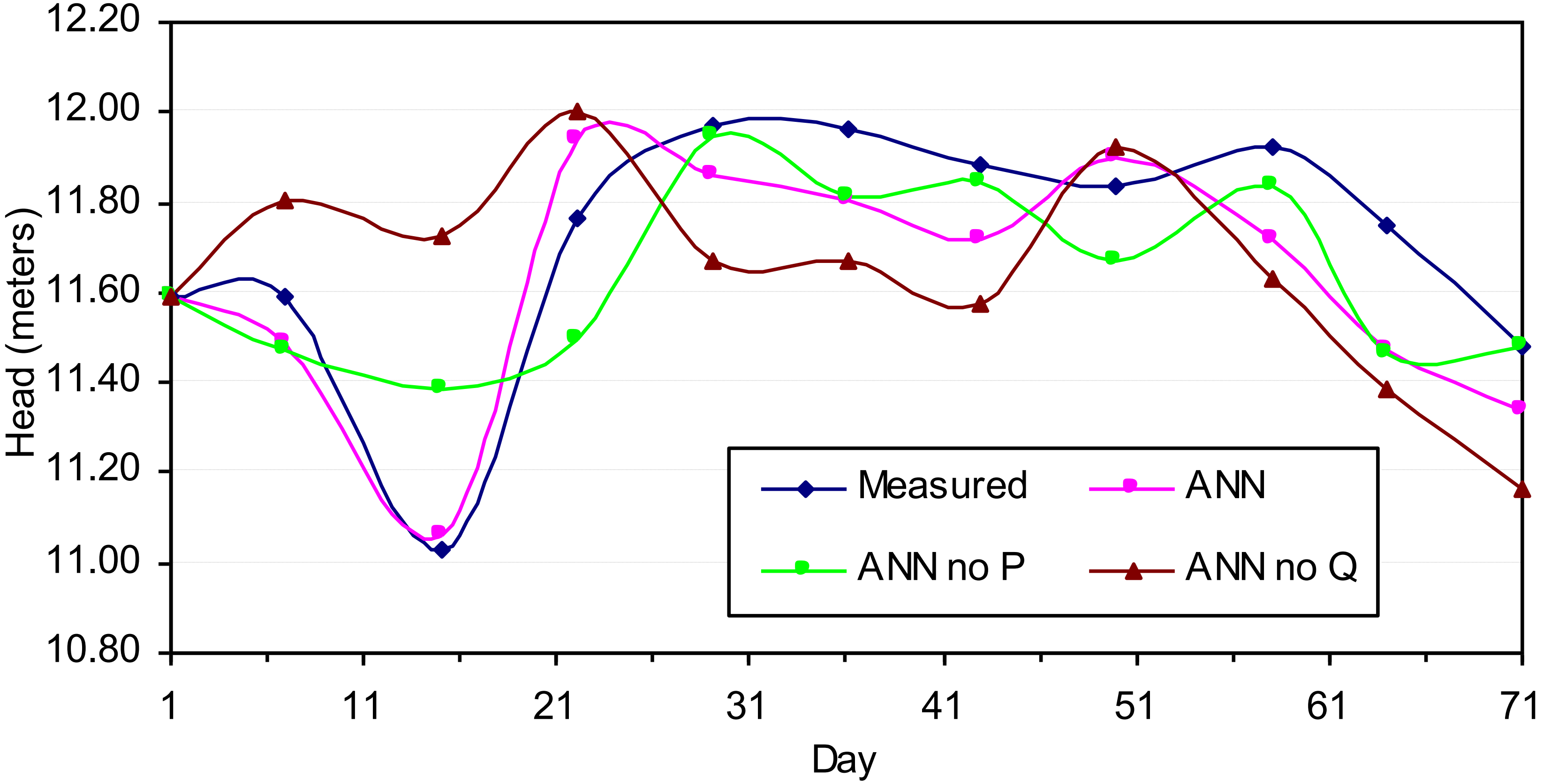
Semi-Confined Aquifer - Validation



SENSITIVITY ANALYSIS
Unconfined Aquifer



SENSITIVITY ANALYSIS
Semi-Confined Aquifer

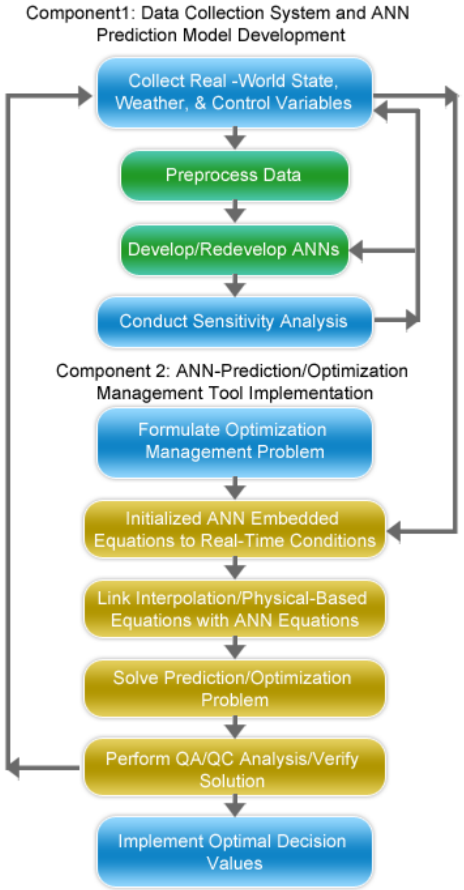


Possible Applications in Southwest U.S.

- Water resources are diminishing and over-stressed
- Population is growing
- Climate change is introducing uncertainty and probably reducing runoff
- More accurate models needed for predicting surface water conditions like flows and stage as well as groundwater elevations in response to variable weather and human use conditions.

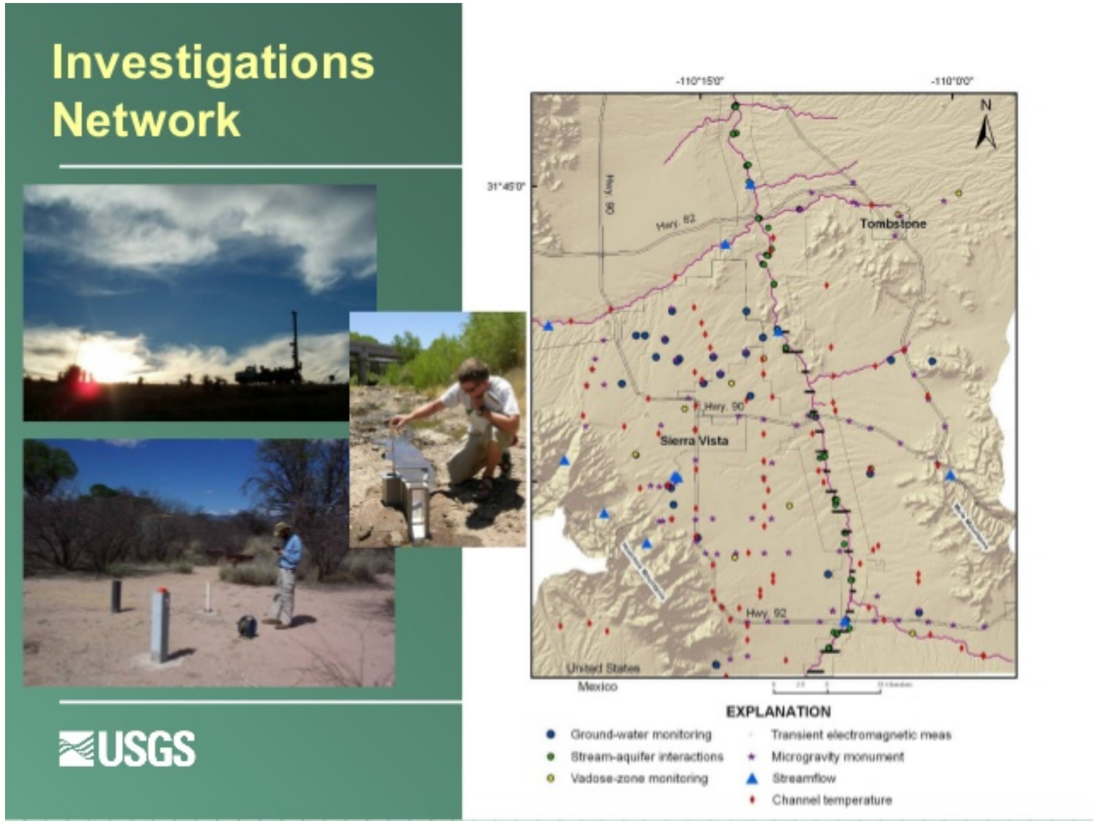
ANN and Optimization

- Use the AI models to perform any number of simulations for different scenarios.
- Integrate the AI simulation/prediction models with formal optimization to identify optimal solutions for different conditions.
- Perform stochastic optimization when uncertainty is included.
- Perform multi-objective optimization where the trade-off curve among conflicting objectives is delineated.



Patented NOAH System

San Pedro River Basin



- Develop AI models to predict groundwater elevations and surface water flows.
- Use historical weather and water use data.
- Use historical groundwater and surface water data.
- Use satellite data.

Discussion & Questions