What is a Model?

1 Types of Models

1.1 Physical Lab Model

Description: A tangible, scaled representation of a real-world system used for experimental testing. Examples include flume experiments for river hydraulics and wind tunnel tests for aerodynamics.

1.2 Interpretive Model

Description: A framework used to explain or assign meaning to observed phenomena. Example: A geological interpretation of past climate conditions from sediment cores.

1.3 Perceptual Model

Description: A mental model or intuitive framework that influences how scientists or practitioners interpret data and processes.

1.4 Statistical Model

Description: A probabilistic framework describing relationships between variables, incorporating uncertainty.

$$P(Y|X) = \frac{P(X|Y)P(Y)}{P(X)}$$

Kriging, for example:

1.5 Empirical Model

Description: A model based purely on observed data rather than first principles. Often expressed as a fitted function.

$$y = ax + b$$

variogram models, for example

1.6 Machine Learning Model

Description: A flexible data-driven model that learns patterns from data, often using neural networks or decision trees.

$$\hat{y} = f(X; \theta)$$

1.7 Conceptual Model

Description: A simplified, qualitative representation of a system, often expressed as flowcharts or box-and-arrow diagrams. Example: The water cycle model.

Linear Reservoir Model: A simple conceptual hydrologic model where the outflow Q is proportional to the storage S:

$$\frac{dS}{dt} = I - Q$$

where: - S is the storage in the reservoir (e.g., groundwater, lake, or soil moisture). - I is the inflow (e.g., precipitation, recharge). - Q is the outflow, assumed proportional to storage:

$$Q = \frac{S}{K}$$

where K is the reservoir **response time** (a storage coefficient with units of time).

Discrete Solution: Using **forward Euler approximation**:

$$S^{n+1} = S^n + \Delta t(I^n - Q^n)$$

Substituting $Q^n = S^n/K$:

$$S^{n+1} = S^n + \Delta t \left(I^n - \frac{S^n}{K} \right)$$

Outflow Update:

$$Q^{n+1} = \frac{S^{n+1}}{K}$$

where: - S^n is storage at time step n. - Q^n is outflow at time step n. - Δt is the time step.

This equation provides a simple way to track how water moves through a storage unit (e.g., watershed, aquifer) using time-stepping.

1.8 Physical Model (PDE-Based)

Description: A computational simulation using physical laws, often represented as partial differential equations (PDEs). Used in climate models, fluid dynamics, and geophysics.

$$\frac{\partial u}{\partial t} = \alpha \frac{\partial^2 u}{\partial x^2}$$

where: - $u(x, t)$ is the temperature at position x and time t. - α is the thermal diffusivity.

1.9 Physical Computer Model (PDE-Based)

Description: A computational simulation using physical laws, often represented as partial differential equations (PDEs). Used in climate models, fluid dynamics, and geophysics.

$$\frac{u_i^{n+1} - u_i^n}{\Delta t} = \alpha \frac{u_{i+1}^n - 2u_i^n + u_{i-1}^n}{\Delta x^2}$$

Solution Update: Solving for u_i^{n+1}:

$$u_i^{n+1} = u_i^n + \frac{\alpha \Delta t}{\Delta x^2} \left(u_{i+1}^n - 2u_i^n + u_{i-1}^n \right)$$

where: - u_i^n is the temperature at grid point i and time step n. - Δt is the time step size. - Δx is the spatial step size.

2 What Are Models Used For?

2.1 Reconstructing the Past (Hindcasts)

Example: Using tree rings to infer past climate conditions.

2.2 Understanding the Present (Nowcasts)

Example: Real-time flood models predicting river discharge.

2.3 Predicting the Future (Forecasts)

Example: Weather forecasting using atmospheric models.

2.4 Interpolating (Filling in the Gaps)

Example: Using kriging to estimate missing spatial data.

2.5 Extrapolating to Unknown Events

Example: Projecting sea level rise based on ice sheet dynamics.

2.6 Understanding the Physical World

Example: Modeling plate tectonics to understand earthquake hazards.

2.7 Analyzing Counterfactuals

Example: Simulating the impact of removing a dam on river flow.

2.8 Attributing Influence from Variables, Events, or Forcings

Example: Determining the role of CO_2 in historical climate change.

2.9 Identifying Causal Relationships

Example: Using statistical inference to assess how deforestation affects local precipitation.