Integrated Hydrologic Modelling with MIKE SHE

HYDROEUROPE, Sophia-Antipolis, February 2011

Julie Landrein, DHI Denmark
- Short presentation of DHI
- Hydrological cycle and integrated hydrology
- MIKE SHE a modelling framework
- MIKE SHE Input Data
- When should I use MIKE SHE?
- MIKE SHE the modelling process - Conceptualisation
- Wrap-up
DHI originally = Danish Hydraulic Institute

DHI exists since 1964

DHI is an independent, international, self-governing research and consultancy organisation

DHI builds competence and promotes technological development relevant to the water, the environment and the health

DHI has ongoing activities world-wide

DHI has a total staff of 1000+ over more than 25 countries

DHI is a leader in HydroInformatics
Introduction to DHI

DHI executes **specialist projects** world wide in more than **140 countries**

DHI collaborates with **leading universities** world wide

DHI is Collaborating Centre for **WHO**, **UNEP**, and Advisory Centre for the **Global Water Partnership**

DHI Software **MIKE** is the global leading water modelling software platform

Also laboratory standards, plus field and physical lab equipment
Modelling the World of Water

Water Resources

- Reservoirs
- MIKE BASIN
- MIKE 21C
- MIKE 11
- MIKE SHE
- FEFLOW

Bays/Estuaries
- MIKE FLOOD

Groundwater
- Urban
- MIKE URBAN
- MIKE 21C
- MIKE 11
- MiKE URBAN

Rivers

Sewers/Pipes

Ports and Harbours
- MIKE 3
- LITPACK

Shorelines

Bays/Estuaries

Treatment

Urban

Marine

Offshore

Quantity, Quality, and Policy
WELCOME
- to the DHI Group

DHI is an independent, international consulting and research organization. Our objectives are to advance technological development and competence within the fields of water, environment and health. We offer a wide range of consulting services and leading edge technologies, software tools, chemical/biological laboratories and physical model test facilities as well as field surveys and monitoring programmes. We are more than 950 employees worldwide.

DHI OFFSHORE RENEWABLES WEBSITE

DHI provides the services required to plan, design, install and maintain offshore renewable energy installations worldwide.

Visit our new website and find all necessary information about DHI Offshore Renewable services, from the early feasibility studies to the detailed environmental impact assessments.

Visit www.offshorerenewables.dhigroup.com

NEWS

08 FEB 2011
CAN POLLUTED WATER TRAVEL UPSTREAM? ...

10 JAN 2011
BREAKING DOWN THE BREAK ...

07 JAN 2011
FIRST TROPICAL BALLAST WATER TEST FACILITY OPENS IN SINGAPORE ...

21 DEC 2010
HYDRA-LAB IV - MORE THAN WATER ...

16 DEC 2010
WOMEN'S WATER FUND - CALL FOR APPLICATIONS ...

10 DEC 2010
DONATION TO WOMEN'S WATER FUND ...

30 NOV 2010
SINGAPOREAN INNOVATION AWARD 2010 ...

09 NOV 2010
STATE OF THE ART MODELLING FOR AUSTRALIAN GROUNDWATER ...

08 NOV 2010
A1T ATTAINS THE STATUS OF AN INTERNATIONAL INTERGOVERNMENTAL ORGANIZATION ...

A healthy environment is our nature
- Short presentation of DHI

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- When should I use MIKE SHE?

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- Wrap-up
The Water Cycle

The natural Water Cycle is

• driven by solar energy

• in equilibrium

• closed
Water Users

Agriculture Users
- Manure spreading
- Irrigation
- Runoff
- Infiltration
- Livestock waste

Urban/Industrial Users
- Transpiration
- Municipal sewage treatment plant
- Soil
- River
- Sanitary landfill
- Hazardous waste
- Underground storage tank

Environmental Users
- Evaporation
- Wetland

What is water consumption/use?

The movement of water from one storage to another

or

The prevention of a competing use
Scale: Basin/Watershed/Subwatershed

The Grand River Watershed
Population: 1 million
Drainage Area: 7000 km²

Laural Creek Sub-watershed
Population: 100,000
Drainage Area: 70 km²

Great Lakes and Basin Lands
Population: 40 million
Drainage Area: 500,000 km²
Subsurface scales
Runoff depends on land surface
- Land use, vegetation, soil type
- Elevation, topography, slope
- Drainage network (e.g., surface ponds)

Runoff depends on meteorology
- Precipitation type - rain, snow
- Intensity, duration, spatial distribution, prior amount
- Air temperature, wind, relative humidity, etc.

An integrated model partitions rainfall into runoff, infiltration, and ET.
Integrated Hydrologic Modelling

Groundwater and land use in the water cycle

- Evapotranspiration
- Runoff
- Water levels
- Stream bed conductance
- Fixed Head
- Wells
- Saturated (Groundwater) Zone
- No Flow

Add Rivers
Add Unsaturated Zone
Add Land Surface
No Flow
Add Rivers
Add Unsaturated Zone
Add Land Surface
No Flow
Add Rivers
Add Unsaturated Zone
Add Land Surface
No Flow
Add Rivers
Add Unsaturated Zone
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The purposes of a hydrologic response model are:

1. To reproduce past events
2. To predict future events and evaluate rare events
3. To evaluate changes on the hydrology
4. To improve our understanding
- Short presentation of DHI
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MIKE SHE – Integrated catchment modelling

Groundwater and Surface Water
One Water — One Resource — One Model
Integrated water quality

Precipitation and snowmelt
Vegetation based evapotranspiration and infiltration
Unsaturated groundwater flow

Saturated groundwater flow

Channel flow in rivers and lakes (MIKE 11)
Demand driven irrigation
Overland surface flow and flooding

Rain and Snow
- Canopy interception
- Net precipitation
- Snow melt
- Infiltration
- Root zone
- Unsaturated flow
- Moving water table

Evapotranspiration
- From intercepted water
- From soil and water surfaces
- From root zone

Pumping and Recharge

Lakes

Overland Flow

Channel Flow

One Water — One Resource — One Model
Integrated water quality
The SHE Story

**Systeme Hydrologique Europeen (SHE)**
- Consortium from mid 1970s
- Inspired by Freeze and Harlan
- 1st commercial version mid 1980s

**MIKE SHE up to 1990**
Physically based process descriptions
= conservation of mass and momentum
= physically meaningful model parameters

**CHANNEL FLOW**
⇒ 1D diffusive wave

**OVERLAND FLOW**
⇒ 2-D diffusive wave

**EVAPOTRANSPIRATION**
⇒ Kristensen & Jensen

**UNSATURATED ZONE FLOW**
⇒ Full 1D Richards Equation

**SATURATED ZONE FLOW**
⇒ 3D Darcy flow
Framework for hydrologic modelling

Conceptual
- Catchment water budget
  - Parameters specified by catchment
    (e.g. discharge)
  - Pro: Does not require catchment data
  - Con: Relies heavily on calibration (e.g. discharge)
  - Con: Not suited for scenario analysis

Physics based
- Conservative of mass and Momentum
  - e.g. Darcy’s Law
  - Pro: Uses available catchment data, thus less dependent on calibration
    - Parameters specified on grid
  - Pro: Well suited for scenario analysis
  - Con: Often not enough data

Distributed

Lumped
Physics based methods often **not** required for every process. Simpler methods faster and require less data.
Evapotranspiration
- From Snow, Canopy, Ponding, Soil, Roots, Groundwater
- Depends on UZ

Snow melt
- Degree-day
- Elevation corrections
- Wet and dry storage
- Partial cell coverage
MIKE SHE – flexible process descriptions

2D Finite Difference

- Diffusive wave sheet flow
- Infiltration, evaporation and 2-way river exchange
- Controlled by surface roughness

Catchment-based

- Cascading topographic zones
- Infiltration, evaporation and 1-way river exchange
MIKE SHE – flexible process descriptions

1D Finite Difference
- Richards equation
  - very non-linear
- Gravity flow
  - no capillarity
  - faster

2-layer Water Balance
- 1D Conceptual
- Root zone + below roots
- For shallow groundwater
- Fast
MIKE SHE – flexible process descriptions

3D Finite Difference
- Grid independent geology input
- Uniform horizontal grid
- Drainage routing

Linear Reservoir
- Catchment-based
- Interflow and baseflow reservoirs draining to rivers
MIKE SHE – flexible process descriptions

1D Channel Flow
- St Venant approx
- Detailed dynamics
- Structures and their operation

Flow Routing
- Flow only
- Fast, longer time steps
- Long simulations

Channel Flow (MIKE 11)
- 1D St Venant Equations:
  - Kinematic wave approx.
  - Diffusive wave approx.
  - Fully dynamic
  - Higher-order fully dynamic

Flow Routing:
- No-routing
- Muskingum
- Muskingum-Cunge

Groundwater Flow
- 3D Finite Difference - Darcy Flow
- Lumped, Conceptual - Linear Reservoir
**MIKE SHE – flexible process descriptions**

**Water Quality**
- All hydrologic processes
- 1st-order decay
- Kinetic sorption-desorption with hysteresis
- Dual domain mass transfer
- Ecolab
Different

- Spatial scales
- Time scales

Processes mixed as required

Explicit coupling

Time scales independent and automatically controlled
A Modelling Framework

- Model independent data entry
- Numerical model generated at run time
- Comprehensive output tools

Databases

<table>
<thead>
<tr>
<th>End day</th>
<th>LAI</th>
<th>Root</th>
<th>Kc</th>
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<tbody>
<tr>
<td>90</td>
<td>2</td>
<td>1.2</td>
<td>0.55</td>
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<tr>
<td>180</td>
<td>4</td>
<td>1.3</td>
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<tr>
<td>270</td>
<td>5.5</td>
<td>1.7</td>
<td>0.55</td>
</tr>
<tr>
<td>365</td>
<td>3</td>
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MIKE 11 (Surface Water)

Mouse (Sewers)

Irrigation Rules

Time Series Data

Gridded Data

GIS/map Data

Preprocessing

Run

Evaluate Output

Model Set Up

MIKE SHE Engine

Stream Hydrographs

Time plots

Map plots

Calibration Statistics

Complete Water Balance
A Modelling Framework

- Preprocessing
- MIKE 11 (Surface Water)
- MOUSE (Sewers)
- Irrigation Rules
- Databases
- MIKE SHE Engine
- Transient particle tracking
- Solute transport
- Post-processing
- Time Series Data
- Gridded Data
- GIS/map Data
- Parameter Estimation
- Uncertainty analysis
- Calibration
- Model Set Up
- Run
- Output
- MIKE 11 (Surface Water)

### Databases

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MIKE SHE User Interface

Data centered structure preserves your data integrity and investment

Dynamic Model Browser and Data Tree

- Logical and intuitive work flow
- Flexible, fully scaleable solution
- Model independent conceptual model

Water budget summary from MIKE SHE
Widely used around the world

Wetland Restoration

Source water protection

Urban drainage

Water Resources Management

Flood Forecasting

Wetland Restoration

Source water protection

Urban drainage

Water Resources Management

Flood Forecasting
Hydrologic Modelling with MIKE SHE

- Short presentation of DHI
- Hydrological cycle and integrated hydrology
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- MIKE SHE Input Data
- When should I use MIKE SHE?
- MIKE SHE the modelling process - Conceptualisation
- Wrap-up
Data – Hydraulic boundaries

Potential Evapotranspiration (mm)

Water Table Depth (m)

Water Level (m OD)

SB e
SB g
SB h

SB e
SB g
SB h
Data – Physical properties

Profile of a Hockley soil series. Hockley soils are excessively drained soils formed in glacial fluvioglacial deposits of stratified sand and gravel.

Photo by P. Fletcher (USDA-ARS)

Ap, 10YR 3/2, Sandy loam.
Bw1, 10YR 5/8, gravelly sandy loam.
Bw2, 10YR 5/6, gravelly loamy sand.
C1, very gravelly coarse sand.
C2, sand.
C3, gravelly coarse sand.
Data Requirements

Groundwater

Physical Properties
- Hydraulic Conductivities
- Specific Yield and Storage
- Subsurface geometry

Hydraulic Boundaries
- Flow and head boundaries
- Pumping rates
- Groundwater recharge
Data Requirements

Streams

Physical Properties
- River bed roughness
- River geometry

Hydraulic Boundaries
- Surface runoff
- River water levels/inflows
## Data Requirements

### Groundwater + Streams + Unsaturated Zone

<table>
<thead>
<tr>
<th>Physical Properties</th>
<th>Hydraulic Boundaries</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hydraulic Conductivities</td>
<td>Flow and head boundaries</td>
</tr>
<tr>
<td>Specific Yield and Storage</td>
<td>Pumping rates</td>
</tr>
<tr>
<td>Subsurface geometry</td>
<td><strong>Surface infiltration</strong></td>
</tr>
<tr>
<td>River bed roughness</td>
<td>Surface runoff</td>
</tr>
<tr>
<td>River geometry</td>
<td>River water levels/inflows</td>
</tr>
<tr>
<td>River bed conductance</td>
<td></td>
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<tr>
<td><strong>Soil properties (e.g. ( \theta_s, \theta_{fc}, K_s ))</strong></td>
<td></td>
</tr>
<tr>
<td>Topography</td>
<td></td>
</tr>
</tbody>
</table>
Data Requirements

**Groundwater + Streams + Unsaturated Zone + Land Surface**

**Physical Properties**
- Hydraulic Conductivity
- Specific Yield and Storage
- Subsurface geometry
- River bed roughness
- River geometry
- River bed conductance
- Soil properties (e.g. $\theta_s$, $\theta_{fc}$, $K_s$)
- Topography
- Runoff properties (e.g. Roughness)
- Vegetation properties (e.g. LAI, root depth)

**Hydraulic Boundaries**
- Flow and head boundaries
- Pumping rates
- Precipitation
- Evapotranspiration
- River water levels/inflows

An integrated hydrologic model internalizes “boundary conditions”
- Short presentation of DHI
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Applications:
- Wetland management
- Conjunctive water utilization
- Climate change impacts
- Land use change analysis
- Catchment nutrient balances
- Irrigation management
- Drought and flood planning
- Urban drainage and groundwater interaction
- Environmental river flows

Basically:
How and where does ALL the water flow? When will it get there and what will it be like?
Dynamic, finite element groundwater model with flexible geometry, advanced water quality, and heat/density flow

Applications:
- Groundwater management
- Groundwater remediation
- Coastal groundwater (salt water intrusion)
- Thermal energy storage and recovery
- Complex geology
- Mining and underground tunnelling
- 3D seepage analysis (dams)

Basically:
How and where does groundwater flow?
When will it get there and what will it be like?
Principle Applications:

- River hydrodynamics
- Structure/reservoir operational control
- Water quality (e.g. wetlands, salinity)
- Sediment transport & morphology
- Flood studies (e.g. mapping, hazard assessment)
- Flood forecasting (on-line, real-time)
- Dam break
- Sediment transport (e.g. Long term morphology)
- River restoration
- Integrated with groundwater and flooding

Application range is still very large!!
Dynamic, combination of linear, channel flow and 2D surface flow

Applications:
- Floodplain hydrodynamics
- Flood forecasting
- Operational control during flood events
- Hazard assessment and mitigation
- Flood mapping
- Storm surge analysis

Basically:
How and where does surface water flow during a flood?
<table>
<thead>
<tr>
<th></th>
<th>MODFLOW</th>
<th>FEFLOW</th>
<th>MIKE SHE</th>
<th>MIKE FLOOD</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Groundwater Only</strong></td>
<td>****</td>
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<tr>
<td><strong>Groundwater + Streams</strong></td>
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<tr>
<td><strong>Groundwater + Streams + Unsat.</strong></td>
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<tr>
<td><strong>Groundwater + Streams + Unsat. + Land.</strong></td>
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<tr>
<td><strong>Salt water intrusion (SZ)</strong></td>
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<td><strong>Heat flow (SZ)</strong></td>
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<td><strong>Geometric / Local constaints (SZ)</strong></td>
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<tr>
<td><strong>Integrated water balance</strong></td>
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<tr>
<td><strong>Catchment hydrology</strong></td>
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<tr>
<td><strong>Regional dynamic recharge</strong></td>
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<tr>
<td><strong>Flood hydraulics</strong></td>
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<tr>
<td><strong>Flood hazard / Dam break assessment</strong></td>
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<tr>
<td><strong>Flood water management</strong></td>
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<tr>
<td><strong>Rejected recharge/Groundwater flooding</strong></td>
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</table>
Suitable when:
Primary focus is on groundwater
  – Groundwater boundaries must be well defined
  – Limited surface water interaction (e.g. confined aquifer)

Steady-state or quasi steady-state (e.g. seasonal)
  – Average results based on average boundary conditions
  – Transient reactions (e.g. Changes in pumping)

• Often restricted area of interest (e.g. well field)
• Least data requirements
• Calibration restricted to groundwater heads
Modelling **Groundwater + Streams**

**Suitable when:**
Primary focus is on groundwater
– Surface water interaction limited to baseflow/infiltration

Quasi steady-state or long term transient
– Monthly or seasonal models

- Often restricted area of interest (e.g. well field)
- Moderate data requirements
- Calibration (mostly) restricted to groundwater heads
- Runoff and infiltration must be externally provided
Fully Integrated Modelling

Suitable when:
Focus on catchment hydrology, including stream flow
- Timing, distribution, quantity, quality
- Recharge and stream dynamics

Groundwater and surface water tightly coupled
- Wetlands, conjunctive use, stream flow depletion

Land use and/or climate are dynamic

Complex irrigation, surface water management

- Area of interest usually whole catchment
- High data requirements
- Balanced calibration required
- Short presentation of DHI
- Hydrological cycle and integrated hydrology
- MIKE SHE a modelling framework
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- When should I use MIKE SHE?
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- Wrap-up
A model must be **designed** and **built** for a purpose.
• Conceptualization is the **art** in modelling

• The conceptualization depends on the purpose

• If your conceptual model is wrong...
Do we need all these processes?
Groundwater and land use in the water cycle

Do we need all this mess?
All the complexity?
Data

Define the purpose

Build a conceptual model

Gather data for the model

- Data is **biased**
- Data has **errors**
- Data is **incomplete**
- Data must be **managed**
- Data is **living**
Set Up

- Define the purpose
- Build a conceptual model
- Gather data for the model
- Set up the model

- Start **simple**
- Keep the model **running**
- Complexity is very hard to remove
Calibration

1. Define the purpose
2. Build a conceptual model
3. Gather data for the model
4. Set up the model
5. Calibrate the model

- All models are wrong. **How wrong could it be?**
- All models must be calibrated
- Can only calibrate the sensitive parameters
- No model can do everything
Validation

- Define the purpose
- Build a conceptual model
- Gather data for the model
- Set up the model
- Calibrate the model
- Validate the model
The modelling process

Define the purpose

Build a conceptual model

Gather data for the model

Set up the model

Calibrate the model

Validate the model

Use the model

Update the model

There is no best model—only the latest model
There is no perfect model $\rightarrow$ Complexity = Cost

Trade off: Time/expense vs precision (not accuracy)

Simplest model that allows you to make a decision

"We do not seek the truth from models, simply engineering confidence"

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Hydrology Recap

• Hydrology is a closed cycle
• Scale is important – space and time
• Groundwater and surface water linked
  – Runoff/Infiltration, and
  – Streambed exchange
• Users compete for the same water, but have different needs and impacts
• Climate and Land use are changing
Hydrologic Modelling Recap

• Fully integrated hydrologic modelling is necessary for modern water resources management
• No perfect model
• Modelling requires simplification
• Modelling involves trade offs
  – Time and expense vs precision (not accuracy)
• Models must be developed to fit the purpose
• Choose the simplest model that allows you to make a decision
MIKE SHE - Recap

• MIKE SHE has a long history

• MIKE SHE
  – is a complete hydrologic model
  – simulates water flow and water quality
  – includes multiple process models
  – has a flexible, data independent user interface

• MIKE SHE is widely used in diverse projects around the world