Hydrological Modelling
with
Green Kenue™ and WATFLOOD™

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Nicholas Kouwen PhD., P.Eng., FASCE

Mackenzie River delta North of Inuvik
Bennet Dam – Williston Lake
Peace River west of Fort St. John – Halfway River Junction
Halfway River junction
Peel River -- Wernecke Mountains (?)
Nahoni Range -- Peel River -- Wernecke Mountains
Dempster Highway – through Richardson Mountains??
Peel River crossing near Fort McPherson
Mackenzie River ferry at Arctic Red River
Modelling objectives for WATFLOOD™

• Flood forecasting and flood studies
• Continuous modelling – climate change impacts
• Ability to model very large as well as small domains
• Ability to optimally use gridded data sources e.g.. Land cover, DEM’s, NWP model output, Radar data
• Universally applicable parameter set (maybe)
• Quick turn around (for a distributed model)
• **Ability to model a wide variety of landscapes**
On choosing a model:

- You would choose WATFLOOD if its particular capabilities are advantageous – e.g.:
  - Highly spatially variable radar of numerical weather model input
  - Climate change scenarios
  - Modelling ungauged basins
  - Modelling very large regions
  - Calibration/validation with point state variable data e.g. SWE
  - Isotope model (only watershed O\textsuperscript{18} & 2H model in existence!!)
  - Extensive wetland/bank storage
  - Intricate hydraulics (lakes & reservoirs)
  - **Pre & Post Processor: GreenKenue**
Distributed vs. Lumped models

With WATFLOOD the measurable quantities for each cell are:

• Bankfull cross sectional area
• Channel slope
• Overland slope
• Cell elevations (min, mean, max)
• Channel classification
• Channel length (in grid)
• Cell connectivity (channel or lake routing)
• % area of each hydrologically similar land cover (GRU)
• Water & wetland areas
Distributed vs. Lumped models (cont’d)

- For lumped models all these measurable quantities are combined into watershed parameters which vary with the watershed’s makeup of the measurable quantities and are optimized.
- For distributed models, each of these measurable characteristics are explicitly incorporated – thus parameters are not “watershed based”
- **PRO:** Distributed models should be better at predicting flow from ungauged watersheds
- **CON:** There is a cost: Distributed models are more difficult to calibrate and have longer execution time.
WATFLOOD Features

- Watflood is a DISTRIBUTED model (Gridded & GRU)
- Grouped response units (GRU’s): will lead to universal parameter set
- Gridded model:
  - **optimal** use of remotely sensed data
  - **optimal** use of numerical weather data
  - **optimal** use of 1,2 and 3D display facilities (e.g. GreenKenue™)
- Tracer & Isotope model
  - In WATFLOOD we ignore connectivity at the small scale (within cell)
History

- **1972 MNR Ontario.** Original idea was to have a gridded model to coupled with weather radar – no one else interested, EC data not free
- Gridded model turned out to be easily and optimally interfaced with remotely sensed land cover data - GRU’s developed in 1985
- 1993-1998 BC Hydro dam safety study with Numerical Weather Model MC2/WATFLOOD
- 1999 Mesoscale Alpine Project (MAP): MC2/WATFLOOD real-time flow forecast experiment. WATFLOOD used to validate MC2 precip forecast.
- 2004 - 2008 development continued for ensemble forecasting
  - WATFLOOD modified to fully integrate with Green Kenue (ENSIM) (common file formats)
  - Great Lakes model
  - Mackenzie river forecast model – coupled to River1D
- 2008 Manitoba Hydro adopts WATFLOOD for climate change study & planning
- 2012 -2014 MH, OMNR, LWCB, OPG implementing flow forecasting with WATFLOOD & Numerical Weather forecasts
Previous Uses:

- Flow forecasting (1972) – original intent, only now being implemented
- Climate change impacts
- Land use change impacts
- Numerical weather model validation (i.e. watershed = precip gauge)
- Dam safety
• GRU’s
  • need
  • limitations
• No two watersheds are alike!!!!!!

• It is impossible to transfer any but the simplest parameters form one watershed to another (e.g. area, slope, shape, vegetation, channel character all different)

• It just seems way more reasonable to define parameters based on land cover & topography – i.e things you can measure
It is our contention that the use of land cover based parameters makes the model much more robust for modelling ungauged watersheds (see better validation errors in the ASCE paper)
Model setup & calibration

• **GreenKenu™ (GK)** for model setup
  – Few decisions
    • (main one: cell size)
    • Number of land covers to model separately
    • Coding lakes
    • Coupled wetland proportion

• Pre-processors for HYDAT, WISKI, etc. data files
  → GK format files for WATFLOOD
Hydrology

Group Response Unit
- to deal with basin heterogeneity

Hydraulics

Physically Based Streamflow Routing
Parameters are for land cover classes A, B, C & D.

Parameters do not change with percentage of each land cover.

Each cell is represented by a watershed with its own cover allocation.

% cover can change over time !!!
WATFLOOD™
Hydrological Model

3 Zones:
- Saturated
- Unsaturated
- Saturated

- Evapotranspiration & evaporation
- Precipitation
- Interception
- Infiltration
- Surface Ponding
- Surface Runoff
- Interflow
- Lower Zone Flow
- Lake/Channel Flow
- Floodplain
- Wetlands

Recharge
Schematic of the Infiltration Process

Surface Storage

Upper Zone Storage (UZ) (Saturated)

Intermediate Zone Storage (IZ) (Unsaturated)

Lower Zone Storage (LZ) (Saturated)

Ponding

Infiltration

Drainage

Surface flow

Hydraulic Gradient

H

Capillary Potential

Soil Moisture m₀

Wetting Front

LZ Outflow

\[
\frac{dF}{dT} = K\left[1 + \frac{(m-m₀)(Pot + Dl)}{F}\right]
\]
GRU’s & Coupled wetlands - e.g. Finlay River, BC
Each cell has these attributes:

• Cells are numbered from upstream to the outlet (highest to lowest elevation)

• *Evapotranspiration, Snow Melt, Runoff and Recharge is computed for each land cover class in each cell* – GRU method

• Runoff is routed to the stream-coupled wetland and then to the stream channel or lake in each grid

• Channel & Lake flows are routed from cell to cell in downstream direction:
  
  • Channel routing: with KW & Manning’s n
  
  • **Coded** Lake routing: with releases or storage-discharge function

  • **Un-coded** lakes: wide channels to preserve water area in each cell and to dampen flow raised Manning’s n prop’l to water area
Modularity

• separate programming units for:
  – Setup
    • Watershed representation: GreenKenue™
    • Event generation
    • Point data to distributed data conversion for meteorological inputs (distance weighting with radius of influence, damping coefficient & lapse rates OR user supplied)
  – Hydrology/Routing: WATFLOOD™
  – Parameter fitting: DDS
  – Post processing: GreenKenue™, Grapher™, Surfer™, Excel™, etc.
  – Statistical analysis of output: Excel™, other stats software
Interfacing with other models (flavours)

• Gridded model allows 1 to 1 matching of runoff units to meteorological driving data from NWM (eg. EC’s GEM)

• Gridded surface model allows 1 to 1 matching of recharge to groundwater model such as MODFLOW

• Computed river inflows can be accumulated on a reach by reach basis for input to an internal Lake routing module or be written to a file in a format compatible with routing models such as DWOPER, Flow1D, River1D, TELEMAC or some other application (e.g. ice jam model).

• Grid outflow computed with any model can be routed with WATROUTE (a subset of WATFLOOD Code)
Scaling/Domain Size

- WATFLOOD has been used with cell sizes from 1 to 25 km (scale) and for watershed areas from 15 to 1,700,000 km^2 (domain).

- WATFLOOD is not sensitive to cell size as long as there are a sufficient number of cells to maintain the integrity of the drainage system and preserve the variability in the meteorological data.

- Regional model: models multiple watersheds (*WATFLOOD cannot be properly calibrated with one or two flow stations*).
Routing features

• Storage routing (center difference KW solution with variable time steps to satisfy Courant criteria everywhere)
• Coupled stream-wetland routing model
• Lake routing, reservoir operating rules & diversions
• Overbank flow (with different resistance coefficients)
• River, Lake and groundwater initialization based on recession curve of observed hydrographs.
Assumed Channel Section

- Fieldwork is still required to confirm assumed section
- Channel & overbank roughness separately set
Channel Cross-Section - Drainage Area Relationship

\[ XA = a(DA)^b \]
Wetland/Bank Storage Model

coded by Trish Stadnyk
based on PhD by Bob McKillop

BOREAS NSA Fen Site:
South Tabacco Creek
Near Morden, Manitoba
Bank storage is very important here as it is where most water is lost to evapotranspiration.
Wetland model schematic
Does the model work?

i.e. does it model nature?
Physical hydrological reasonableness:

- Where possible, time series of state variables are compared to observed data (e.g. SWE, lake levels, GW levels, soil moisture, O).

- All model components have been individually verified.
Plots are used to check if general principles are ok.

Plot of UZS and LZS

Plots of snow covered area, snow water equivalent and snow pack heat deficit.

Plots of cumulative precipitation, evaporation and runoff.
Compare model swe to snow course observations.
Comparison of snow pillow data and WATFLOOD/SPL SWE estimates
by Janet Wong BCH
Comparison of observed SWE to modelled SWE for the Columbia River basin.

Janet Wong BCH
Upper Zone Storage (UZS) in mm

Field data provided by Joachim Gurtz & Massimiliano Zappa
Analysis by Shari Carlaw
Evaporation comparison for the BOREAS SSA-OBS Tower Site - eddy correlation method

By Todd Neff
Evaporation comparison for the BOREAS NSA-OBS Tower Site

By Todd Neff
WATFLOOD Tracers  (Trish Stadnyk’s stuff)

- **Tracer 0**: Sub-basin separation
- **Tracer 1**: Glacier melt separation
- **Tracer 2**: Land-cover separation
- **Tracer 3**: Rain-on-stream tracer
- **Tracer 100**: Baseflow separation
- **Tracer 4**: Flow separation
  - surface
  - interflow
  - baseflow
- **Tracer 5**: Flow & Snow-melt
  - surface + surface melt
  - interflow + melt drainage
  - baseflow + interflow melt drainage
E.G. Baseflow has been compared to isotope analysis of streamflow sources
An isotope fractionation model has been embedded in WATFLOOD so $\delta^{18}O$ can be calculated and compared to observed $\delta^{18}O$ (also $\delta^{2}H$ now)

The isotope signature is affected by the proportion that water is or is not exposed to evaporation as $O^{18}$ is not evaporated at the same rate as $O^{16}$

If computed and observed $\delta^{18}O$ are close, it ensures that the model’s mass balance is ok and that the GW portion of the flow is correct.

The WSC is collecting water samples for isotope analysis so this data can be used for modelling in the future.

This is a 4 year pilot project 2013-2017
Other checks can be made:

- frequency analysis of observed & computed data can be compared
Illecillewaet River at Greeley
08ND0133
32 years

Legend
- Observed
- Simulated, short series
- Simulated with paf, short series

(By Allyson Bingeman)
Columbia River at Nicholson
08NA002
91 years
Mica Dam
23 years

Legend
- Observed
- Simulated, short series
- Simulated with paf, short series

Probability of Non-exceedance

Flow (cms)
• You can **NEVER-EVER** eliminate errors of computed flows due to the areal variability of precipitation!!!!!!!

• You can reduce errors by improving the representation of the watershed (e.g. landcover/soil based gru’s) and

• Model improvement (e.g. lapse rates, lake evaporation, etc.)
Quality of the precip data: # records / year
Compare annual precip at Mackenzie and Germansen Landing In the Upper Peace River
Plot the annual precipitation for 2 neighboring stations

Only years with data 360 days or more
Do the same for Norman Wells & Watson Lake.
Annual Precipitation mm -- Watson Lake

Only years with data 360 days or more
Only years with data 360 days or more.
And for Yellowknife & Hay River

Only years with data 360 days or more
This should serve to lower expectations a bit!

Coffee maybe?