Modelling semi-arid and arid hydrology and water resources – the southern Africa experience

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Introduction

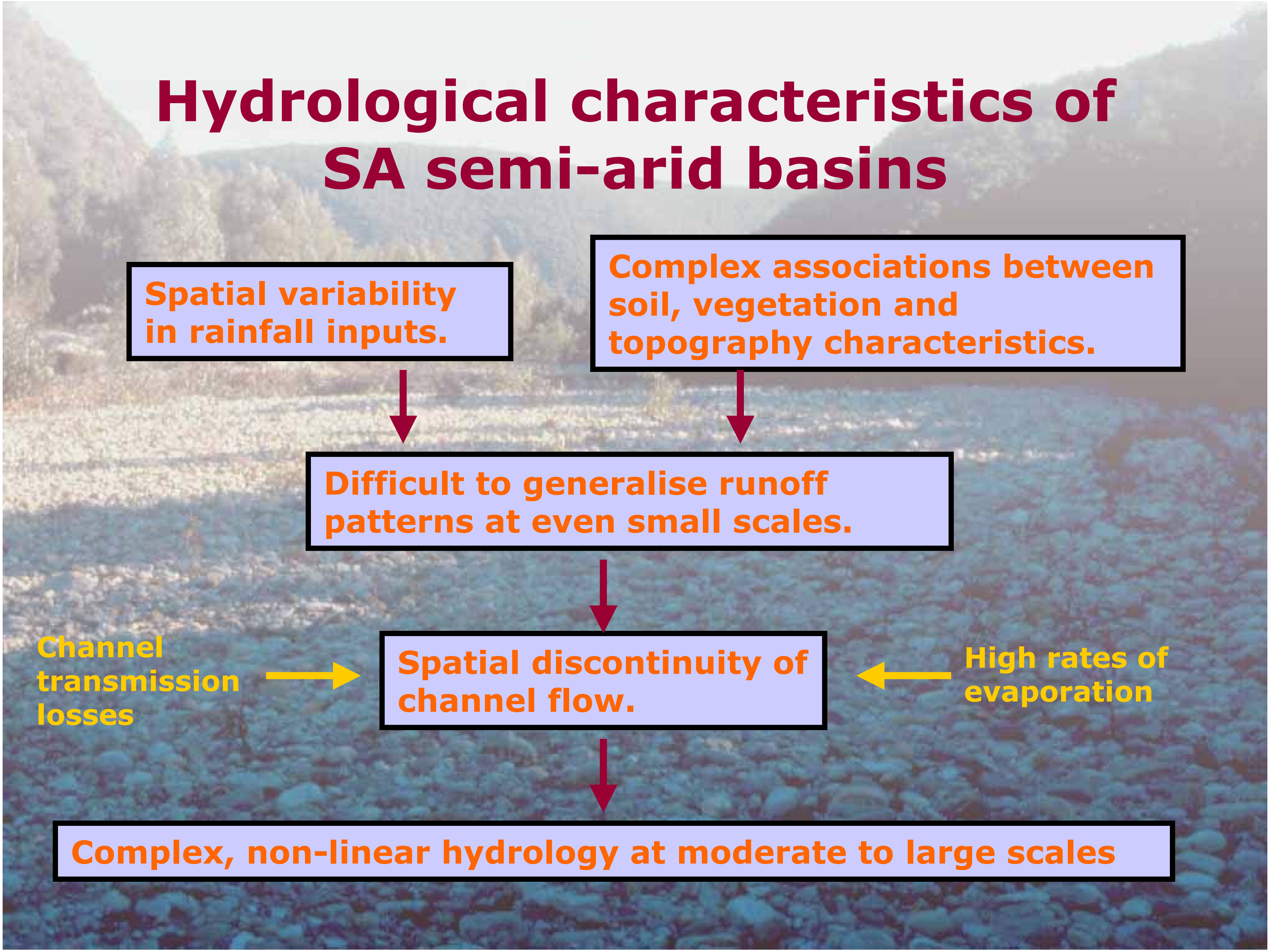
- Large parts of southern Africa are frequently defined as semi-arid on the basis of the balance between rainfall & potential evaporation.

- However, many of these experience perennial streamflow and have characteristics which are more closely similar to humid or temperate regions.

- The focus in this presentation is on those areas with ephemeral channels and are characterised by typical semi-arid processes.

Issues that limit the successful application of models

- **High degree of spatial and temporal variability.**
- **A lack of adequately long or continuous records.**
- **A lack of information on land use and water utilisation changes.**
- **A lack of quantitative understanding of the mechanisms of some critical hydrological processes.**
- **A lack of technical capacity in some parts of the region.**


Hydrological characteristics of SA semi-arid basins
Spatial variability in rainfall inputs.
Complex associations between soil, vegetation and topography characteristics.
Difficult to generalise runoff patterns at even small scales.
Channel transmission losses
Spatial discontinuity of channel flow.
High rates of evaporation
Complex, non-linear hydrology at moderate to large scales

Hydrological processes (contd.)

- **Dynamic vegetation cover characteristics**
  - Wet seasons -> improved vegetation cover
  - Leads to improved infiltration & more effective evapotranspiration losses.
  - Reduced relative runoff in several following seasons.

- **Channel transmission losses**
  - Recognised as very important, but not well quantified.
  - Initial flow has to satisfy in-channel pool storage.
  - Channel flow subject to seepage and evaporation.
  - Riparian vegetation enhances losses from bank storage and alluvial aquifers.
  - Small farm dams further complicate rainfall-runoff relationships.

Hydrological processes (contd.)

- Several basins have their headwaters in wetter areas with perennial rivers and then pass through semi-arid and arid zones.
  - e.g. Orange, Limpopo, Okavango rivers.
- Many of these are underlain by alluvial aquifers, which represent an important water resource during the dry season.
  - Natural losses are difficult to quantify and pumping from the aquifers further complicates the issue.
  - Very little quantitative information is available.

Data availability

- While there exists a relatively sound conceptual understanding of the regions hydrological processes, providing sufficient data to quantify the process is a different matter.
- The political and socio-economic history of the region has not been conducive to the collection and maintenance of hydrological records.
- Despite the recognised importance of well-managed water resources, hydrological data collection is not high on the agendas of many of the regions government institutions.

Data availability - Rainfall

- Semi-arid networks are sparse, despite high spatial variability:
  - Difficulty of access and maintenance.
  - Only daily (at best) observations and very little short-term intensity data.

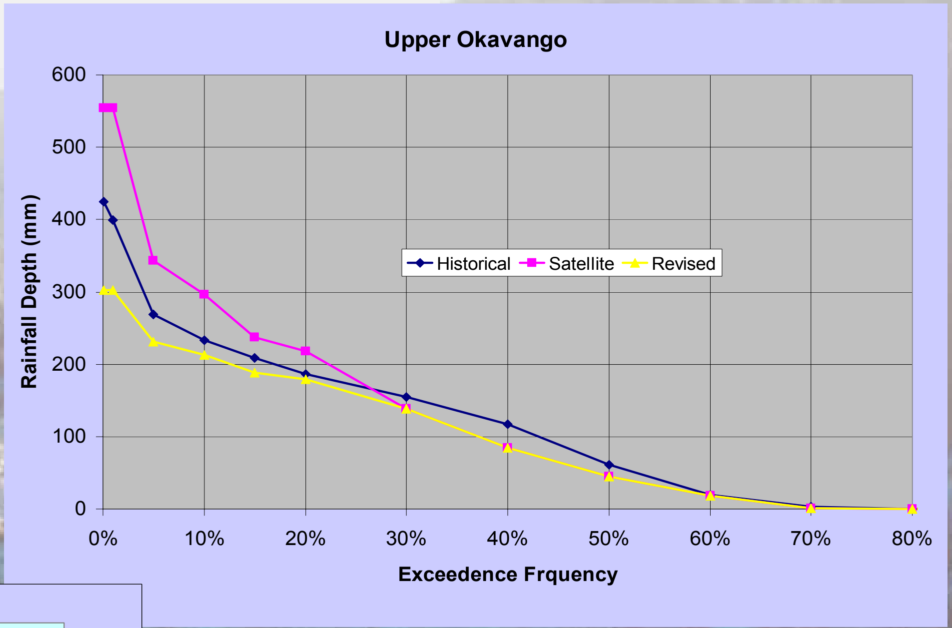
- The future appears to lie in satellite derived data, but these need to be checked for consistency with the available historical records.
  - An example from the Okavango basin suggests that this is not always straightforward.

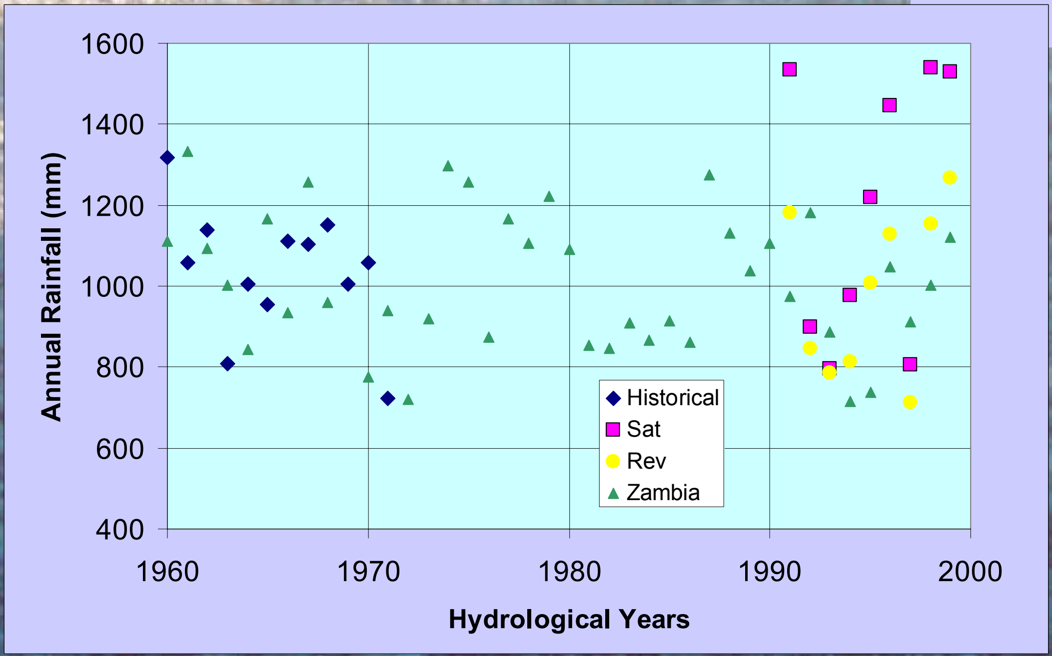
Rainfall – satellite versus historical data

Historical: 1960-1971 ; Satellite: 1991-2001

Non-linear correction to satellite data applied to all sub-catchments in the basin based on rainfall frequency diagrams.

Note that gauged flow data indicates that the later period was drier than the 1960s.





Comparison with continuous Zambian rainfall data at the same latitude.

Historical data for both gauges in the 1960s are similar (pattern and range).

Satellite data in the 1990s are quite different, while revised rainfalls are now in the same range.

When used with a model (calibrated for the 1960s) the revised data give much better results.

Data availability - Evaporation

- Generally a worse situation than rainfall
  - Fewer stations.
  - More missing data.
  - Based on many different observing systems (pans, temperature based, etc.).
- However, for many rainfall events in semi-arid basins runoff generation is not very dependent on antecedent conditions (and therefore the evaporation regime).
- Evaporation data is important for understanding losses from channels and riparian vegetation.

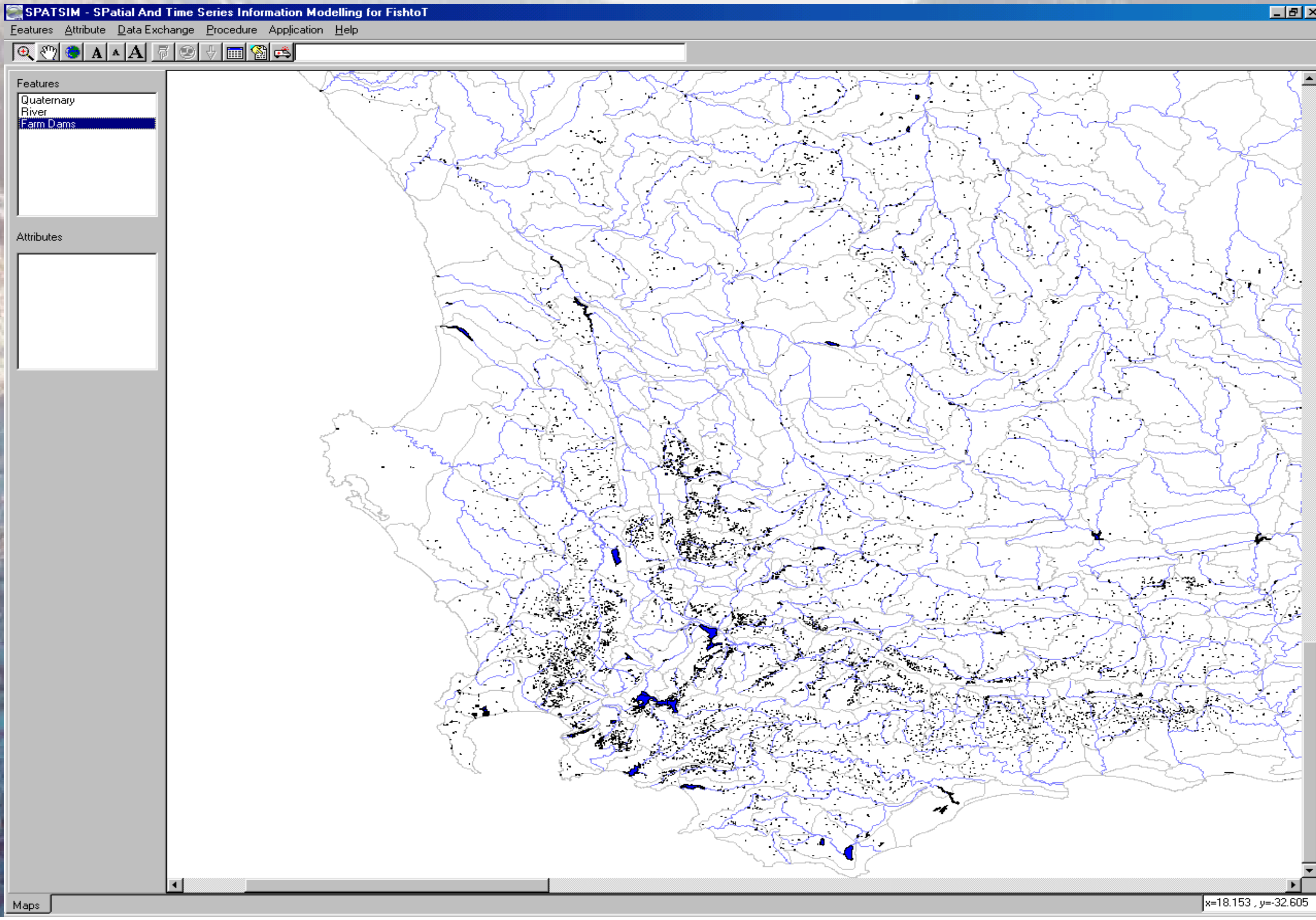
Data availability - Streamflow

- **Some countries use weirs and flumes (South Africa & Namibia) while others rely on rated sections.**
- **All suffer from rating problems, especially at extreme high and low flows.**
- **Lack of maintenance resources means that rating tables are not updated frequently enough.**
- **Poorly quantified land use changes and water abstractions (see next slide) can confuse analyses of observed flow data.**

Data availability – water utilisation and land use data

- Inadequate data on land use changes.
- Small ‘farm’ dams are quite frequent in semi-arid areas, but their impacts are poorly quantified.
- Information on large dams is much better.
- Abstractions from alluvial aquifers and the impact on channel transmission losses are poorly quantified in some areas.

Reservoirs (large and small) in the Western Cape, South Africa

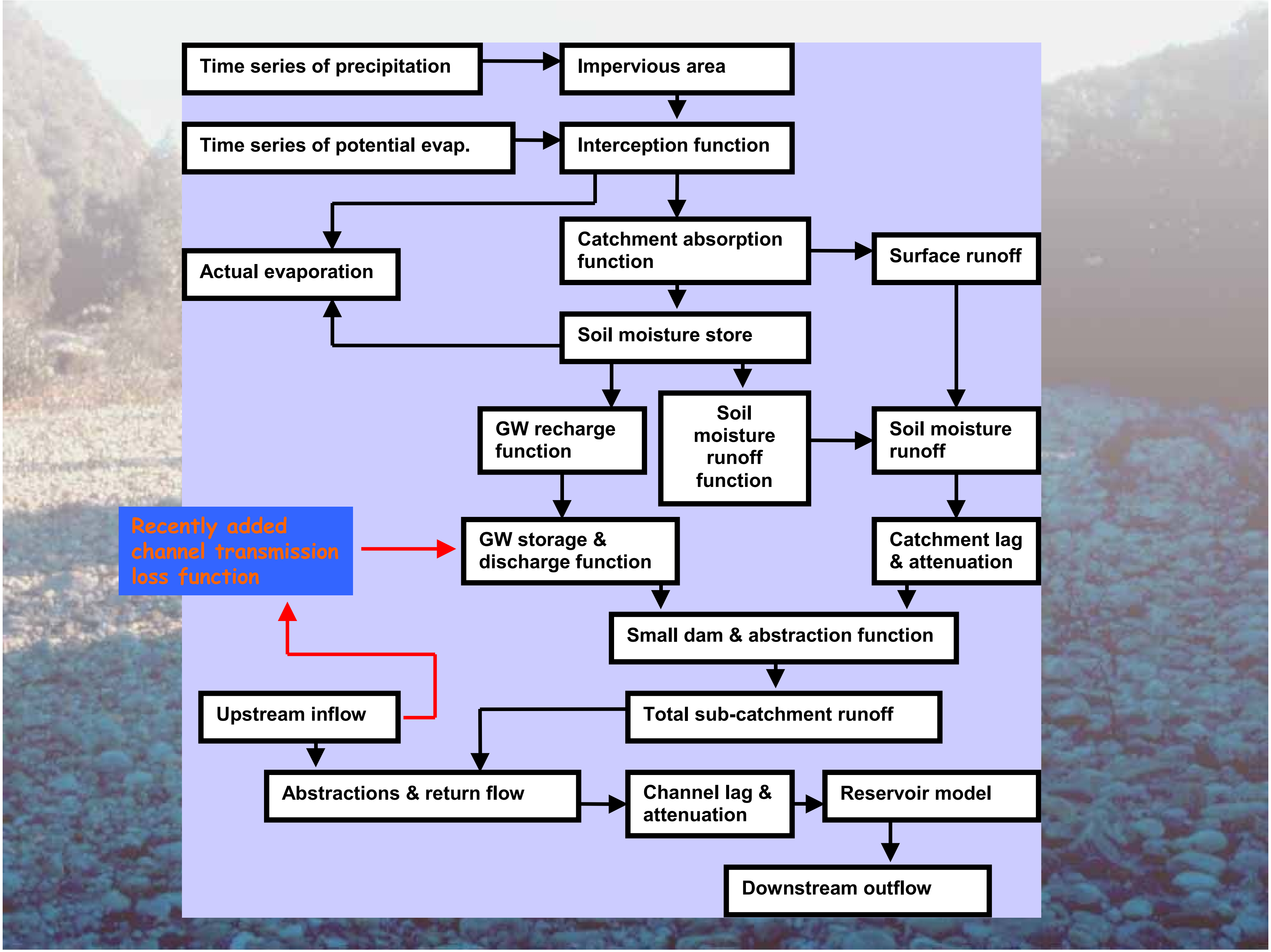


Hydrological modelling approaches

- Most models developed and applied within the region are ‘conceptual’ type, moisture accounting models.
- Most are applied using manual calibration and the use of regionalised parameter sets for ungauged basins.
- Some attempts have been made to develop more direct methods of estimating parameters for ungauged basins.
- Most are continuous time series models (rather than single event flood models).
- Developments have been driven by the pragmatic requirements of water resource engineers rather than research orientated science.

Pitman monthly model

- Probably the most widely used model in the region.
  - Used extensively in South Africa.
  - Applied to most other southern African countries.
  - Tested in the SA FRIEND programme.
- Several versions with various additions to the original 1973 model (e.g. more explicit ground water recharge and discharge functions of Hughes, 2004).
- Can operate using a semi-distributed distribution scheme, where each sub-area has independent hydrometeorological inputs and parameter sets.
- No specific semi-arid process functions but guidelines are available for use in semi-arid areas and channel losses frequently accounted for using 'dummy' reservoirs.



Time series of precipitation
Impervious area
Time series of potential evap.
Interception function
Actual evaporation
Catchment absorption function
Surface runoff
Soil moisture store
GW recharge function
Soil moisture runoff function
Soil moisture runoff
Recently added channel transmission loss function
GW storage & discharge function
Catchment lag & attenuation
Small dam & abstraction function
Upstream inflow
Total sub-catchment runoff
Abstractions & return flow
Channel lag & attenuation
Reservoir model
Downstream outflow

Pitman model

- Easier to apply in temperate than semi-arid parts of the region. Could be ascribed to:
- Poor definition of spatial rainfall variation.
- Limitations of the model :
  - Temporal rain distribution in a single month.
  - Simplistic approach to runoff generation.
  - Simple approach to channel transmission losses.
- To isolate which is the most important would require more observed data than are generally available.

NAMROM model

- Developed in Namibia to specifically account for:
  - Dynamic non-seasonal, surface cover variations.
  - Channel transmission losses.

- Applied with reasonable success in Namibia, but its general applicability is largely untested.

- Tested against the Pitman model for use in determining long-term yields of Namibian reservoirs.
  - Obtained similar calibration (20 year period) statistics.
  - Yield analyses quite different when applied to 68 years of available rainfall data.
  - Illustrates importance of checking long-term applicability of calibrated parameter sets.

ACRU Daily model

- Multi-layer soil moisture accounting model (BEEH, University of KwZulu-Natal).
- Designed to be used without calibration through default relationships with measurable catchment properties (soils, vegetation, management practices, etc.).
- Mostly used in temperate and humid areas with perennial rivers and in frequent use for assessing the impacts of commercial afforestation.
- Not widely used or tested in areas with ephemeral rivers.

VTI (Variable Time Interval) model

- Developed by IWR, Rhodes University with specific functions to deal with semi-arid processes.
- Default daily time step, but can drop to 5 mins if rainfall intensity data are available.
  - Time interval depends on rainfall threshold values.
- Has a large number of parameters, which interact with each other.
- Many parameters are not easy to estimate from known catchment properties and the model is difficult to calibrate and to use in ungauged basins.
- Has been used with some success in Bostwana and semi-arid Zimbabwe basins.

Monash model

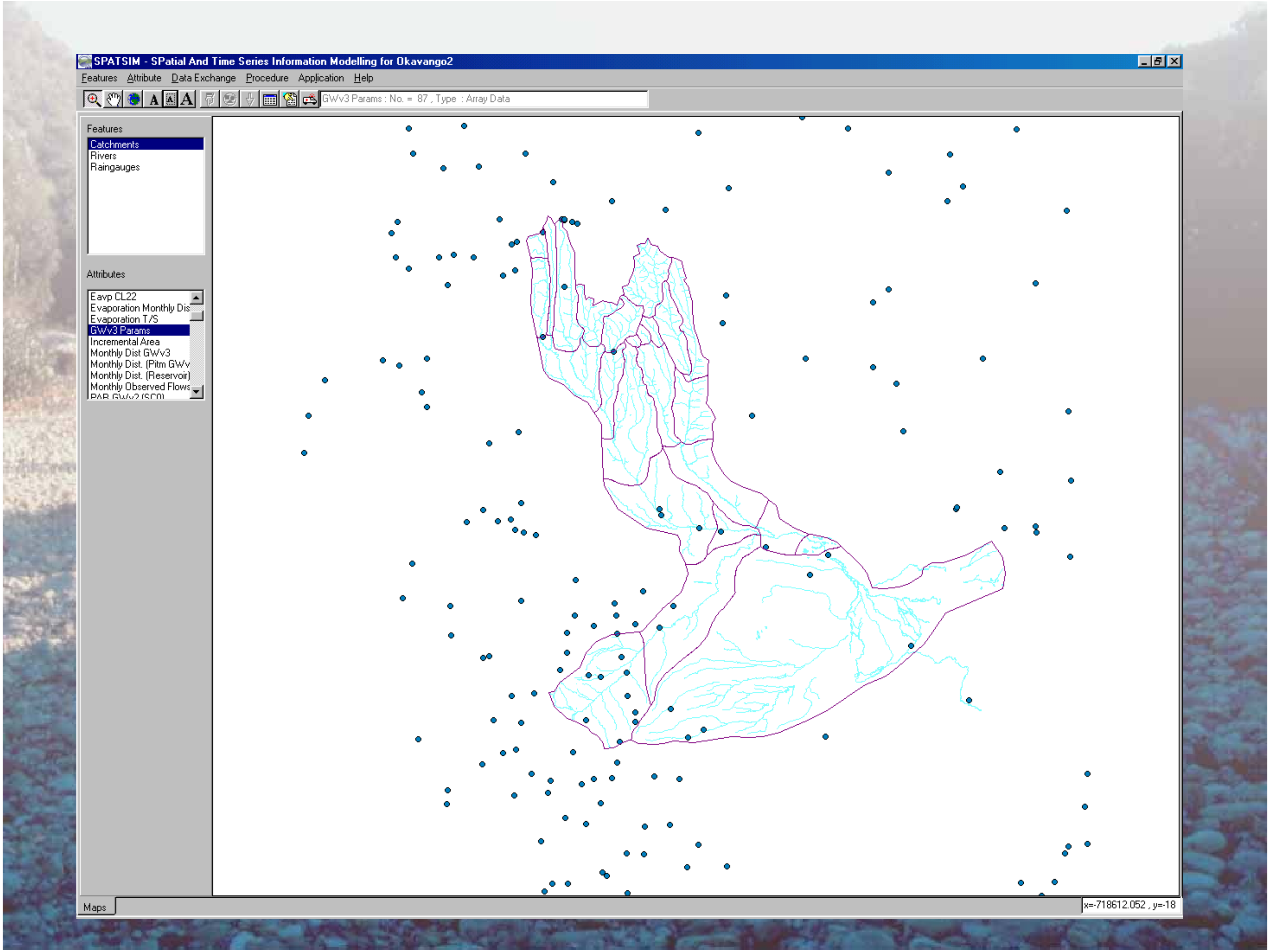
- **SMEC (Australian consultants) applied this daily model to Botswana basins.**
- **Appears to offer some advantages over the original Pitman monthly model.**
- **Not enough detail presented in the results to properly assess the model performance.**

Modelling environments

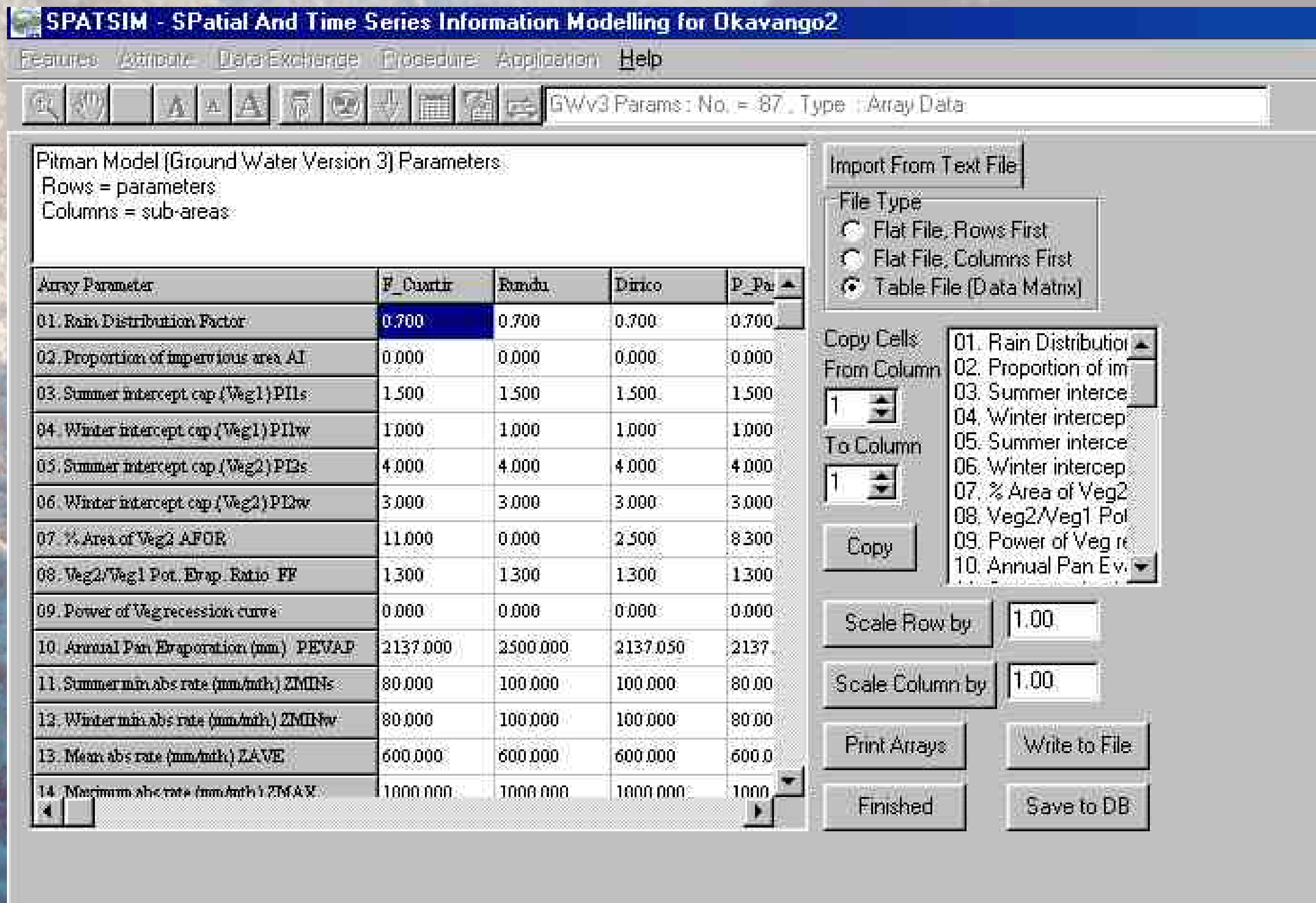
- Lack of access to appropriate models and data processing/analysis tools has been identified as a regional problem.
- Some internationally available modelling environments have seen limited use in the region (e.g. Mike Basins, ArcHydro, etc.)
- IWR, Rhodes University has developed a Spatial and Time Series Information Modelling (SPATSIM) package that is seeing increasing use.

SPATSIM

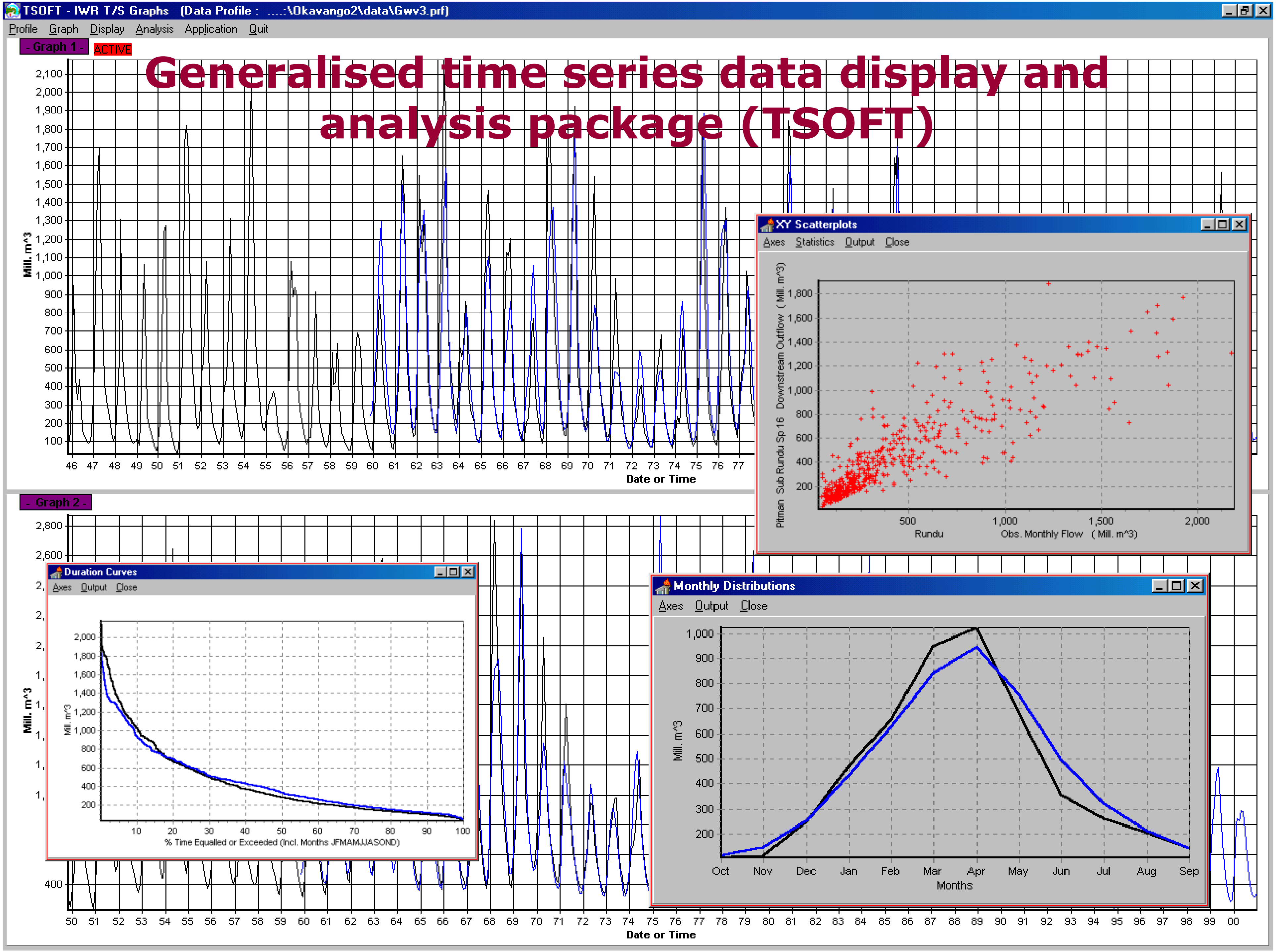
- Developed with Delphi using ESRI Map Objects to provide the spatial interface.
- Data stored in generic database tables for single text, single values, tables of values, memos, graphics and time series data.
- Full range of data import, export, editing and display facilities.
- Efficient links to a range of external hydrology and water resource models.
- Link to a generalised time series display and analysis package (TSOFT).


SPATSIM - SPatial And Time Series Information Modelling for Okavango2
Features Attribute Data Exchange Procedure Application Help
GWv3 Params : No. = 87 , Type : Array Data
Features
Catchments
Rivers
Raingauges
Attributes
Eavp CL22
Evaporation Monthly Dis
Evaporation T/S
GWv3 Params
Incremental Area
Monthly Dist GWv3
Monthly Dist. (Pitm GWv
Monthly Dist. (Reservoir)
Monthly Observed Flows
Maps
x=-718612.052 , y=-18

Editing model parameters or other types of table (array) data



Generalised time series data display and analysis package (TSOFT)



SPATSIM developments

- Used extensively as a consulting tool in South African environmental flow determinations.
- IWMI (Sri Lanka) & IWR jointly developed regional drought analysis procedures.
- SPATSIM to be used as the platform for the update of the regional SA water resource database (WR2005), together with a revised Pitman model.
- Several other developments of models or database applications in South Africa.

Issues and conclusions I

- **Process understanding**
  - One of the main limitations to further model development.
  - Can only expect limited progress, due to a lack of research resources (finances and staff).

  - Limited networks of ground water observations in large-scale alluvial aquifer systems could be useful and only require limited resources.
  - Need to be coupled with improved understanding of evaporative losses from alluvial aquifers.

Issues and conclusions II

- **Available hydrometeorological data**
  - There are clear indications that uncertainty in model results is frequently associated with a lack of representative (in space and time) rainfall data.
  - The prospects for improving ground based observation networks are poor.
  - The future seems to lie in satellite and radar derived estimates (need to be related to historical records).

- **Physical catchment data**
  - Remote sensing methods (as used elsewhere in the world) need to be more widely tested and applied in the region.

Issues and conclusions III

- **Model developments**
  - Existing models have been used successfully in water resource design and management projects.
  - The priorities for practical model applications used to be storage design.
  - Recent emphasis on environmental flows and sustainable development has changed some priorities and reliable low flow estimates have become important.
  - There are additional management issues in semi-arid areas that available models are also less capable of addressing with confidence.

Issues and conclusions III

- Model developments
  - There is a great need for more detailed information and reliable estimates of development or climate change impacts.
  - The existing models do not need to be replaced. In many cases it is the approaches to model use and the emphasis of the calibration process that need modification.
  - Model success depends on appropriate model selection, data quality and user experience.

A pragmatic approach to improving model estimates suggests that there is a need for:

- **Only limited changes to existing models.**
- **Better use of available data, both hydro-meteorological and spatial basin property data.**
- **Improved guidelines for model use (specifically calibration and regional model parameters).**
- **Training of model users.**