Water management options for the Middle Drâa River Basin

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Overview

1. Cropping under erratic water supply
   - the study area
2. The MIVAD hydro-economic model
3. Scenarios of source-dependent water pricing
4. Conclusions and outlook

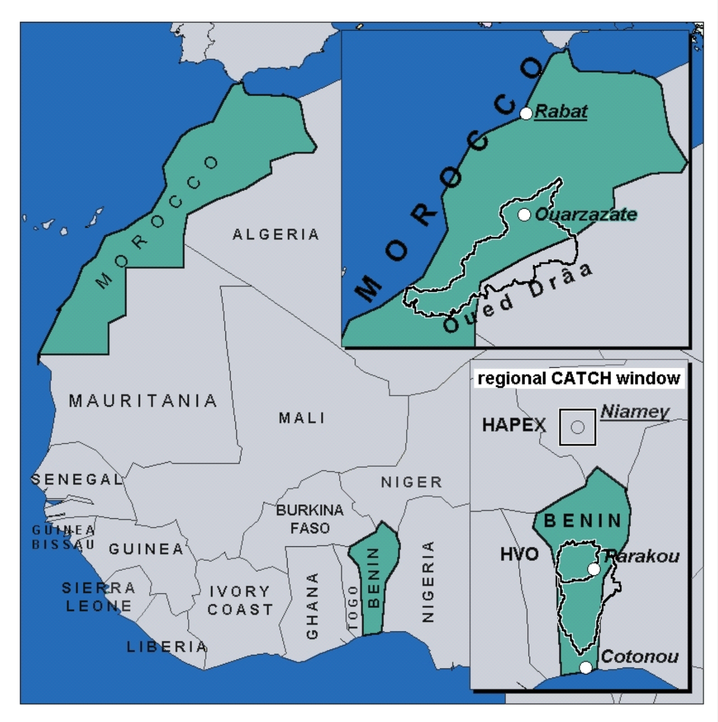
The IMPETUS project

Integratives Management-Projekt fuer einen Effizienten und Tragfaehigen Umgang mit Suesswasser in West Afrika

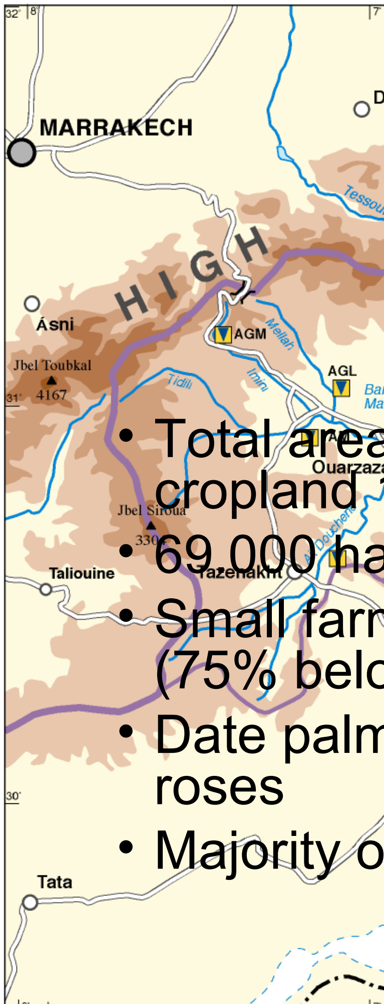
- integrated approach to the efficient management of scarce water resources in West Africa
- investigations of various aspects of the hydrological cycle within two river catchments: wadi Drâa (Morocco) and river Ouémé (Benin)
- financed by German Research Ministry (BMBF)

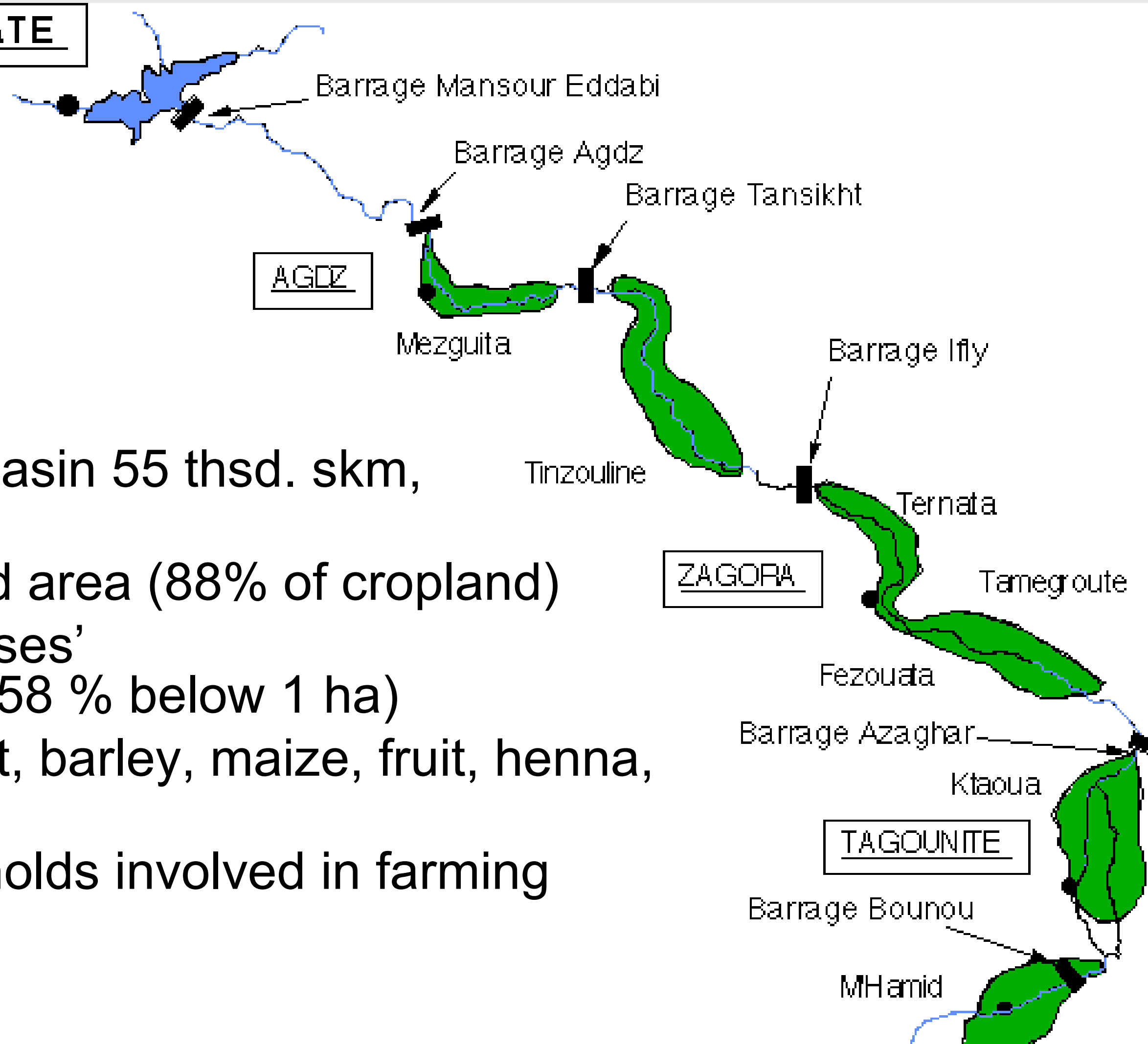
Goals

- understanding the hydrological cycle under different aspects
- modeling of different case scenarios
- set up of a management plan for a sustainable use of fresh water



The Drâa Valley





- Total area of the basin 55 thsd. skm, cropland 1.4%
- 69.000 ha irrigated area (88% of cropland)
- Small farms in 'oases' (75% below 2 ha, 58 % below 1 ha)
- Date palms, wheat, barley, maize, fruit, henna, roses
- Majority of households involved in farming

Some facts about the Drâa valley

- Total population 1.16 Mio, 2.3 percent growth rate
- Majority of households involved in farming
- Tourism, light industry, mining, film industry, handicrafts
- Overwhelmingly important: remittances from labour migrants
- Total area of the basin 55 thsd. skm, cropland 1.4%
- 69.000 ha irrigated area (88% of cropland)
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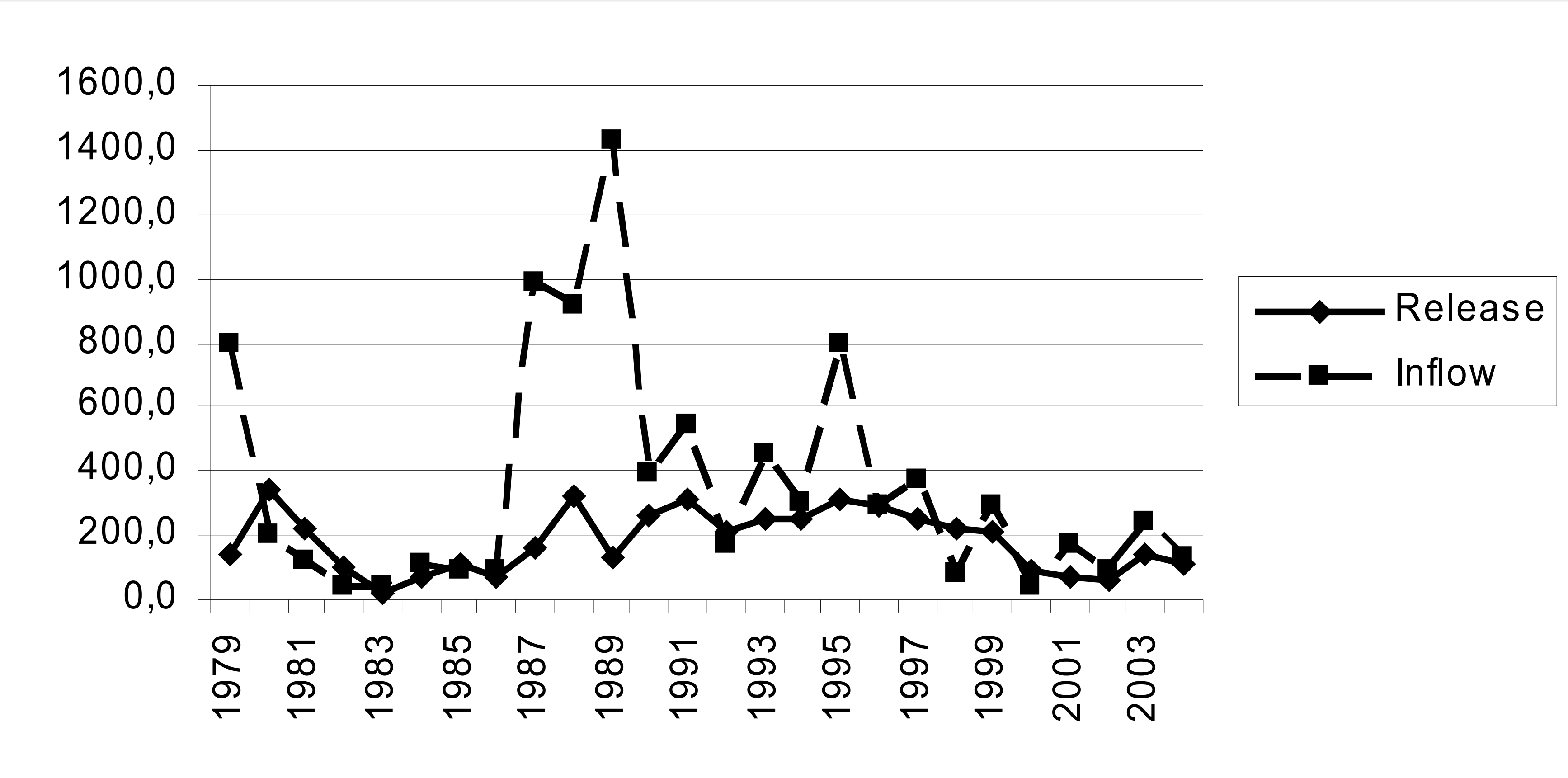
- Date palms, wheat, barley, maize, fruit, henna, roses

Water-related problems

- Highly volatile availability of surface water, declining trend
- More use of groundwater for irrigation
- Increasing problems with salinity
- Competition from non-agricultural users (minor problem!)

Water balance of the Mansour Eddhabi reservoir



- Serial correlation of wet and dry years?
- Droughts of up to a decade well likely …

Gross water storage capacity in the Drâa valley

	1972	2000	2020
Total reserves in mio cbm	918	797	725
Reservoir	61%	55%	51%
Aquifers	39%	45%	49%

- Siltation of the reservoir, high evaporation losses
- Increasing role for groundwater as buffer
- Needs for irrigation: 320 Mio cbm in a normal year

Research tasks

- Consider conjunctive use of water resources within numerical simulation models
- Develop long-term scenarios on the basin scale
- Simulate water management options, among them water pricing
- Goals of water management:
  - Stabilisation of farm incomes
  - Preservation of groundwater resources

The case for managing irrigation water

- More efficient allocation of water among user groups, locations, and time periods
  - Reduce wasteful use of water in the face of increasing scarcity
  - Ease scarcity for non-agricultural users
  - Induce technical innovations
- Reduce negative external effects of misallocation
  - e.g. better water quality
  - Sustaining streamflows (by saving surface water)
  - Preserving landscapes (by saving groundwater)

Management options for irrigation water

- Water pricing
  - volumetric
  - area-based
- Water rights or quotas (non-tradable)
- Water markets (tradable use rights)

Water management in Morocco and the Drâa region

- Pricing of surface water in most irrigation perimeters
- Price levels mostly below cost recovery levels
- No pricing of groundwater use
- In the Drâa region, no water pricing at all
- Local distribution of surface water according to historical farming areas

MIVAD
Hydro-economic river basin model

Modèle intégré de la vallée du Drâa (**MIVAD**)

- Structured as nonlinear optimization problem
- Goal: maximization of agricultural income in the six oases
- Constraints involve yield formation, land availability, and hydrological balances
- ‘Node network’ for spatial representation
- Planning model with fixed market prices and costs
- Extensive dual network of shadow prices

MIVAD
Hydro-economic river basin model

Modèle intégré de la vallée du Drâa (**MIVAD**)

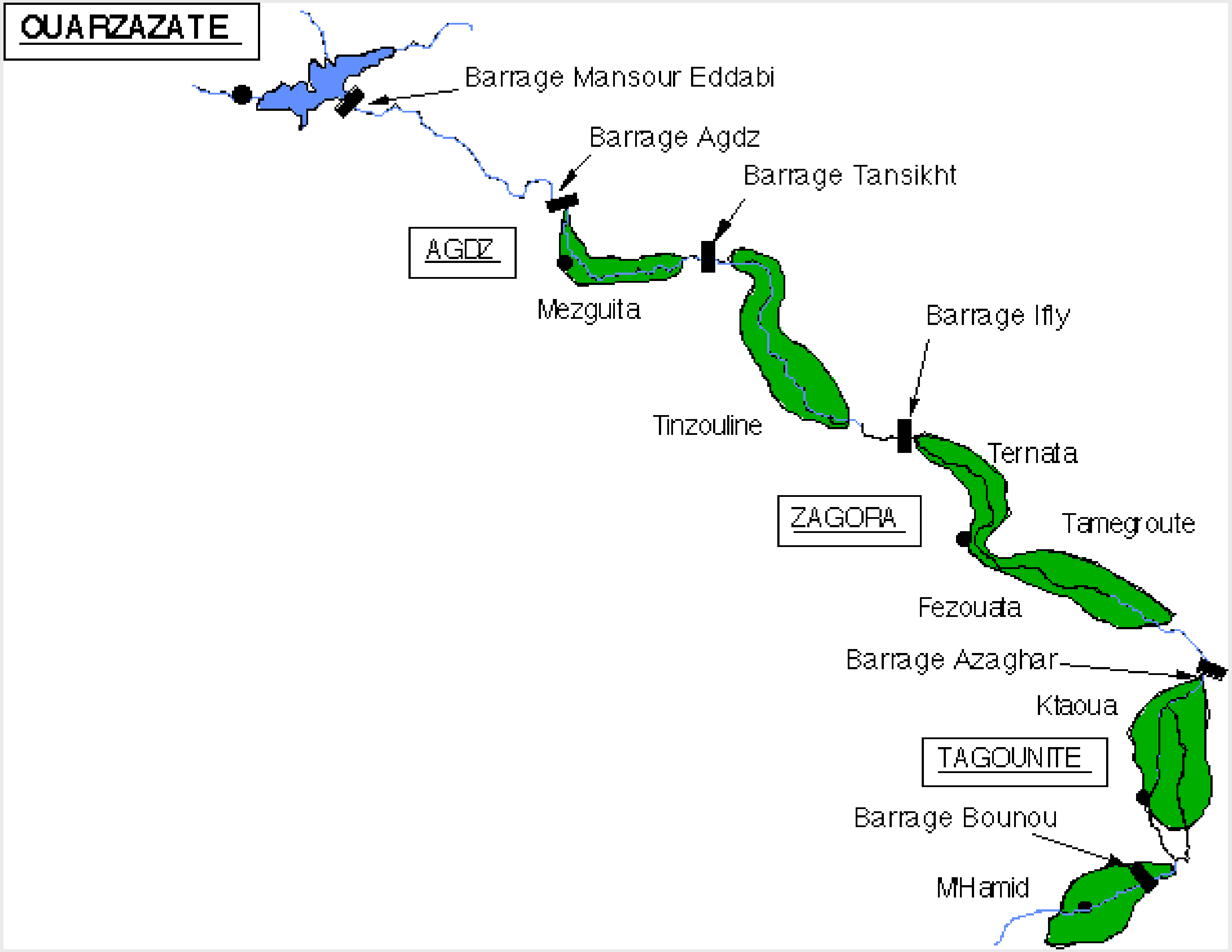
- Eight crops (dates, wheat, barley, corn, alfalfa, henna, beans, vegetables)
- Endogenous yield formation (water application per hectare, non-linear)
- Calibration of crop areas through Positive Mathematical Programming (PMP)
- Simulation period: one year in monthly steps
- Recursive-dynamic over a series of years
- Carry-over of reservoir and groundwater fill levels between simulation years

MIVAD
Hydro-economic river basin model

Modèle intégré de la vallée du Drâa (**MIVAD**)

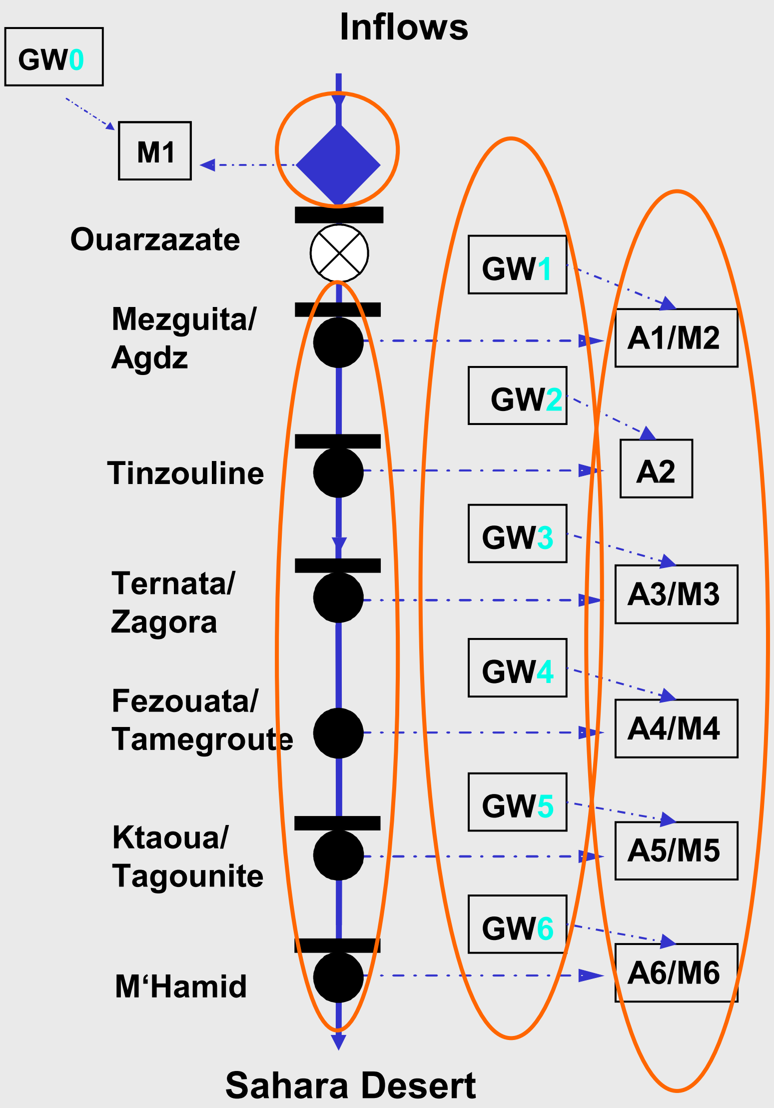
- Nonlinear optimization problem (max. revenues from farming in the basin)
- Planning model with fixed market prices and costs
- Eight crops (dates, wheat, barley, corn, alfalfa, henna, beans, vegetables)
- Endogenous yield formation (water application per hectare, non-linear)
- Simulation period: one year in monthly steps (fully dynamic)
- Recursive-dynamic over a series of years
- Carry-over of reservoir and groundwater fill levels to the next simulation year

Study area => spatial structure

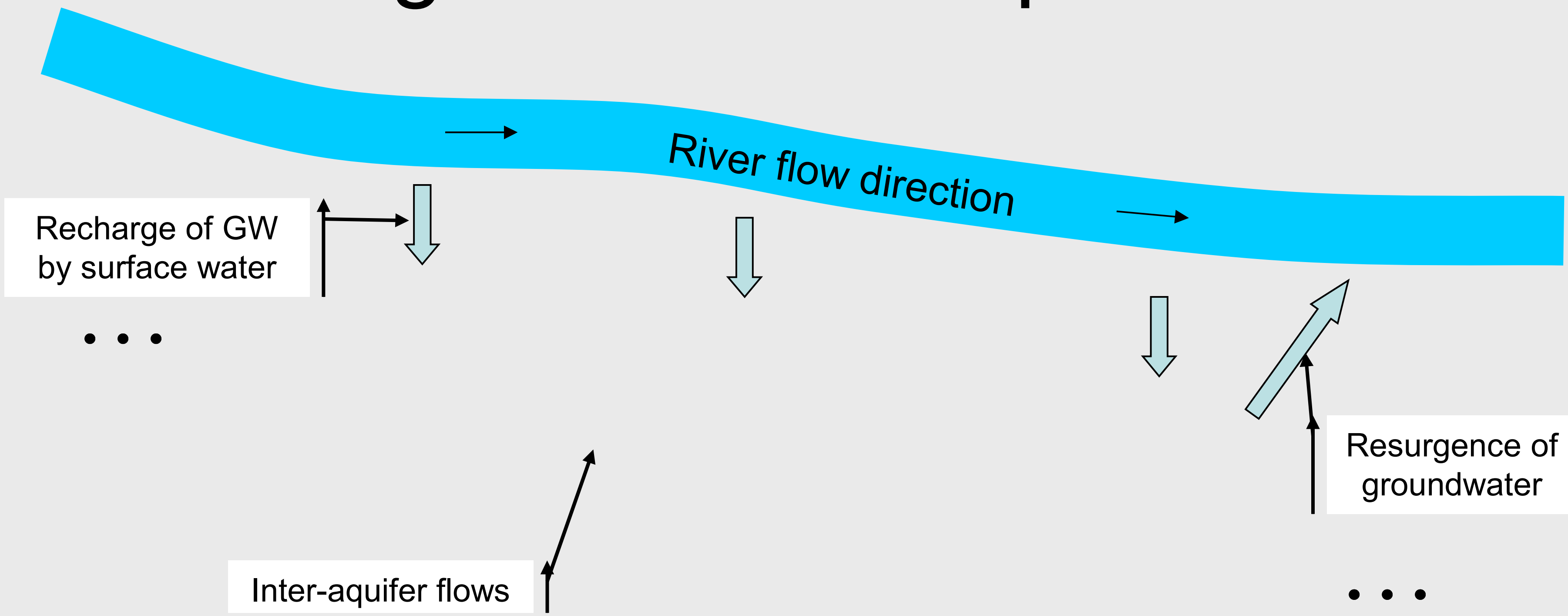


Node network

- Surface water is centrally distributed from the reservoir along the river
- Each demand site has an underlying aquifer
- Groundwater is withdrawn from the local aquifers



Natural interaction between river and groundwater aquifers



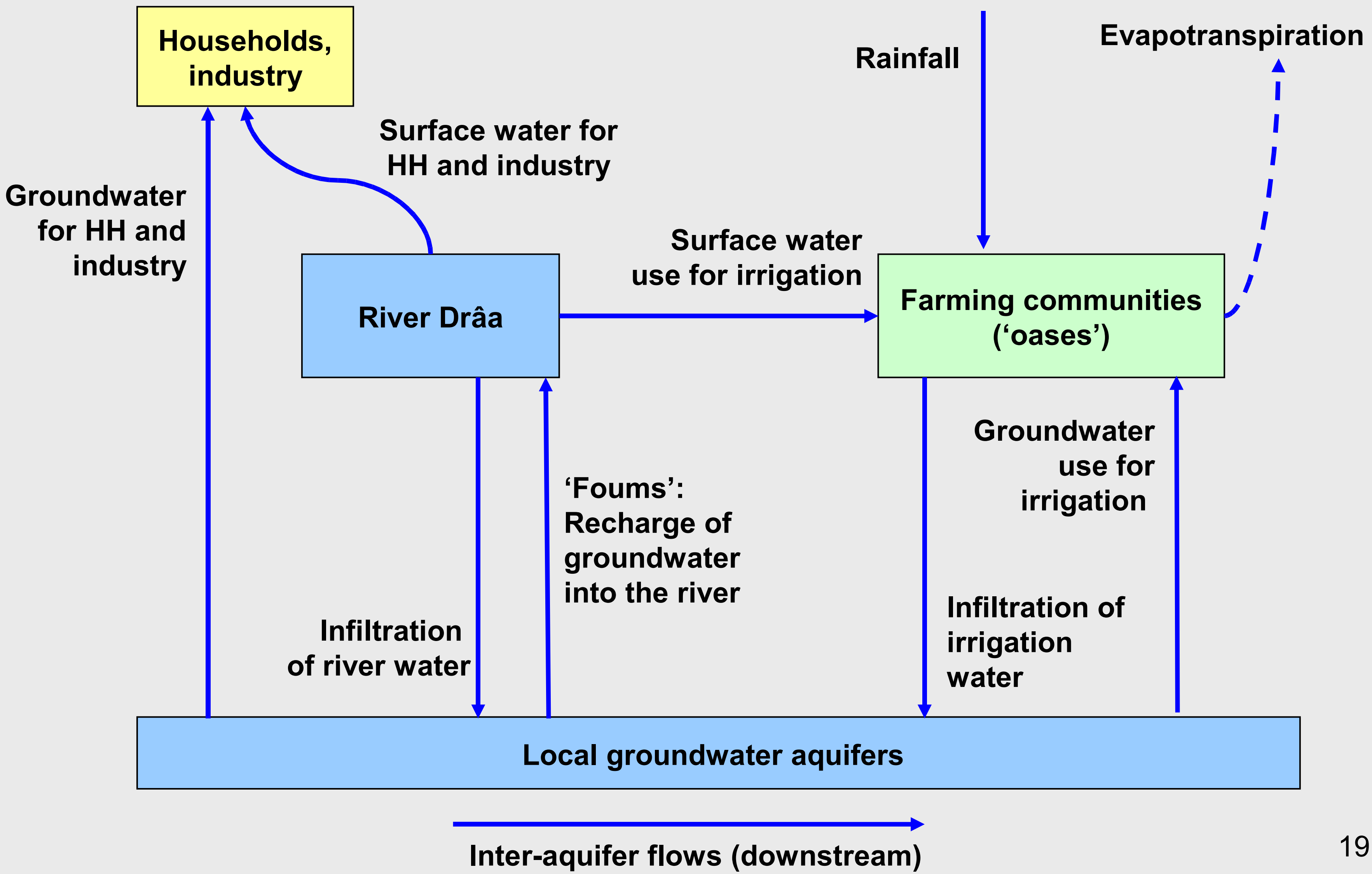
GW2

‚Bathtub' model of aquifers

GW3

Shallow aquifers are mainly fed by the river!

Conjunctive use of water resources



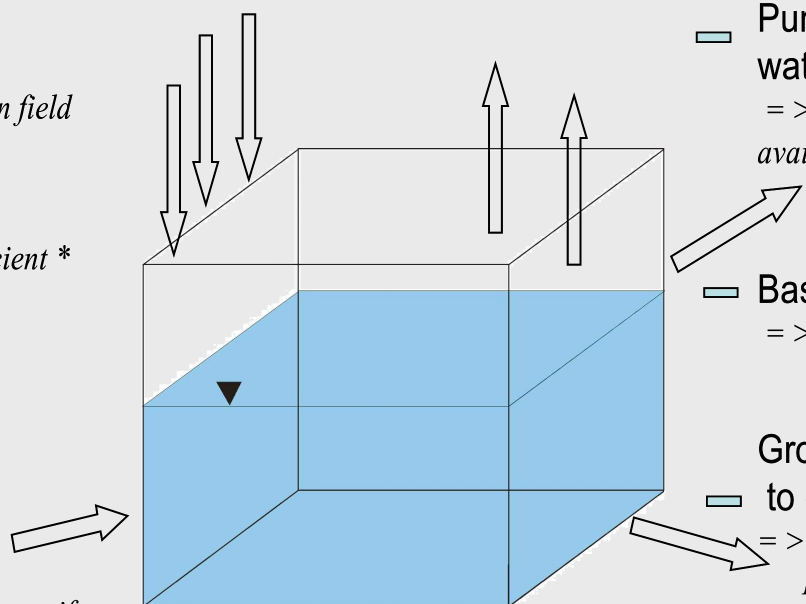
Groundwater Balance

\+ Infiltration of river water
= > Needs to be further determined

\+ Infiltration of irrigation water
= > 40% of applied irrigation water on field

\+ Recharge from rain
*= > Precipitation * Infiltration coefficient * Catchment surface of the aquifer*

\+ Groundwater flow from upstream
= > according to the Darcy Formula:
Hydraulic conductivity
** Hydraulic gradient from upstream aquifer*
** flow section*



– Pumping for municipal water uses
= > f (consumer utility)

– Pumping for agricultural water uses
= > f (marginal crop yields, availability of surface water, etc.)

– Base flow "Spill over"
= > pos. if VGW – GW MAX, non- negative

– Groundwater flow to downstream oasis
= > according to the Darcy Formula:
Hydraulic conductivity
** Hydraulic gradient to downstream aquifer*
** flow section*

Other hydrological balances

- **Reservoir balance**

  (reservoir fill rate * evaporation losses) $_{t-1}$ + inflows_t

  =

  $\text{reservoir fill rate}_t$ + withdrawals

- **River node balance**

  inflows (from upstream river nodes, reservoirs, lateral inflows)

  =

  withdrawals, infiltration into the aquifer, outflow to the next river node

MIVAD‘s optimisation problem

- Use resources such that the sum of agricultural gross margins across farming communities is maximisied

$$\max_{\substack{\text{crop area,}\\ \text{water use}}} \sum_{oases} \sum_{crops} GM_{oasis,crop}$$

by taking into account constraints resulting from:

- agronomy (yield formation due to water application)
- hydrology (hydrologic balances for reservoirs, river nodes, aquifers, and fields)
- exogenous increase of non-agricultural water needs

Encoded in GAMS, NLP-Problem, Solver Conopt3

Derivation of decision variables

FOC for crop area A_i

$$\overbrace{MC_i^L\left(\left(\sum_t \lambda_t^A \cdot W_{i,t}^A\right), \lambda^L, A_i\right)}^{\text{Marginal costs}} \geq \overbrace{MR_i^L\left(\overline{P}_i \cdot Y_i, \overline{AC}_i, A_i\right)}^{\text{Marginal revenues}} \quad \perp \quad A_i \geq 0$$

A_i = crop area

W^A = application of irrigation water per hectare

λ^A = shadow price of water for crop irrigation

λ^L = shadow price of cropland

P_i, Y_i, AC_i, = crop prices, yields, and accounting costs, respectively

Decision variables

FOC for water application per ha
(=> crop evapotranspiration ETA_i => crop yields)

$$MC_i^{irrig}\left(ETA_i^{seas},\overline{ETM_{i,t}^{stage}},\lambda_t^G,\lambda_t^A\right)$$

$$\geq MR_i^{irrig}\left(ETA_i^{seas},\overline{ETM_{i,t}^{stage}},\overline{Y_i^{max}},\overline{ky_i^{seas}},\overline{P_i}\right) \quad \perp \quad ETA_i^{seas} \geq 0$$

ETM_i = yield-maximising monthly evapotranspiration
λ^G = shadow price of groundwater in a local aquifer
$Ymax_i$ = maximum crop yield
ky_i = seasonal crop water deficit coefficient

Decision variables

FOC for <u>reservoir fill level</u> *R*

$$\lambda_t^R \geq \lambda_{t+1}^R \cdot \overbrace{(1 - evap)}^{\text{Share of reservoir fill available in next period}} \quad \perp \quad R_t^R \geq 0$$

evap = evaporation loss factor of the reservoir

λ^R = shadow price for water in reservoir

- High evaporation losses in the reservoir, particularly in summer
- Losses provide a disincentive to store water for later periods

Decision variables

FOC for releases from the reservoir F^R

$$\lambda_t^R \geq \lambda_t^S \quad \perp \quad F_t^R \geq 0$$

λ^S = shadow price of water in a river node (here: adjacent node to the reservoir)

Decision variables

First-order condition for water supply <u>at river node</u> F^S

$$\lambda^S_{f,t} \geq \lambda^S_{f+1,t} \cdot \overbrace{\left(1 - infil^{SG}_{f,f+1}\right)}^{\text{Share of outflows available downstream}} + \lambda^G_{f+1,t} \cdot \overbrace{infil^{SG}_{f,f+1}}^{\text{Share of outflow infiltrating into downstream aquifer}}$$

$$\geq \lambda^S_{f+1,t} - \left(\lambda^S_{f+1,t} - \lambda^G_{f+1,t}\right) \cdot infil^{SG}_{f,f+1} \perp F^S_{f,f+1,t} \geq 0$$

infil = infiltration of river water into the downstream aquifer

- Increasing river-aquifer infiltration will c. p. decrease the incentive of the central planner to deliver water to oases …
- … even more so when λ^G is low or zero, i.e. as long as the downstream groundwater aquifer will not be exhausted in any month within any year

Decision variables

First-order condition for withdrawals at river node W^S

$$\lambda^S_{f,t} + \underbrace{c^S_f}_{\text{Costs / charges of surface water use}} + \underbrace{\frac{\lambda^{distr}_f}{\sum_t W^S_{f,t}} - \sum_f \left(\frac{\lambda^{distr}_f \cdot \sum_t W^S_{f,t}}{\sum_{f,t} {W^S_{f,t}}^2} \right)}_{\text{Opportunity costs of the distribution rules}}$$

$$\geq \underbrace{\lambda^A_{f,t} \cdot \left(1 - loss^{SG}_f\right)}_{\text{Marginal value of irrigation water net of losses}} + \underbrace{\lambda^G_{f,t} \cdot loss^{SG}_f}_{\text{Value of infiltration into the groundwater}} \quad \Leftrightarrow \quad \geq \lambda^A_{f,t} - \left(\lambda^A_{f,t} - \lambda^G_{f,t}\right) \cdot loss^{SG}_f \quad \perp \quad W^S_{f,t} \geq 0$$

loss = infiltration of irrigation water into the local aquifer

Decision variables

First-order condition for aquifer fill levels R^G

$$\overbrace{\lambda^G_{f,t} - \lambda^G_{f,t+1}}^{\text{Intertemporal difference of GW shadow prices in f}} - \overbrace{\lambda^G_{f,t}\cdot darcy\left[R^G_{f,t}, R^G_{f+1,t}\right]}^{\text{Costs of groundwater outflow to the downstream aquifer}} + \overbrace{\lambda^G_{f+1,t}\cdot darcy\left[R^G_{f,t} - R^G_{f+1,t}\uparrow\right]}^{\text{Value of groundwater outflow to the downstream aquifer}} \geq 0$$

$$\leftrightarrow \lambda^G_{f,t} + \left(\lambda^G_{f+1,t} - \lambda^G_{f,t}\right)\cdot darcy \geq \lambda^G_{f,t+1} \quad \perp \quad \overbrace{R^G_{f,t}}^{\text{Fill level of aquifer}} \geq 0$$

darcy = hydrologic function governing inter-aquifer flows

- shadow prices of next period in the same aquifer
- shadow price in the adjacent river node (in the case of discharge into the river)
- shadow price in the downstream aquifer (due to inter-aquifer flows)

=> Under competition, increasing inter-aquifer-flows decrease socially optimal aquifer fill levels … and reward more local pumping

Internal decision rule for pumping of groundwater W^G

$$\underbrace{\underbrace{\lambda^{G}_{f,t}}_{\text{Groundwater's marginal value, opportunity costs of pumping 'here and now'}} + \underbrace{c^{G}_{f}}_{\text{Costs + charges of groundwater use}}}_{\text{Marginal costs of groundwater use}}$$

$$\geq$$

$$\underbrace{\underbrace{\lambda^{A}_{f,t}}_{\text{Irrigation water's marginal value, opportunity costs of use 'here and now'}}}_{\text{Marginal revenue of groundwater use}} \quad \perp \quad W^{G}_{f,t} \geq 0$$

Why use a programming/simulation model?

- Poor data availability
- Complex processes often yield counter-intuitive results
- No observations of pricing experiments possible
- In policy dialogue, magnitudes and figures matter a lot

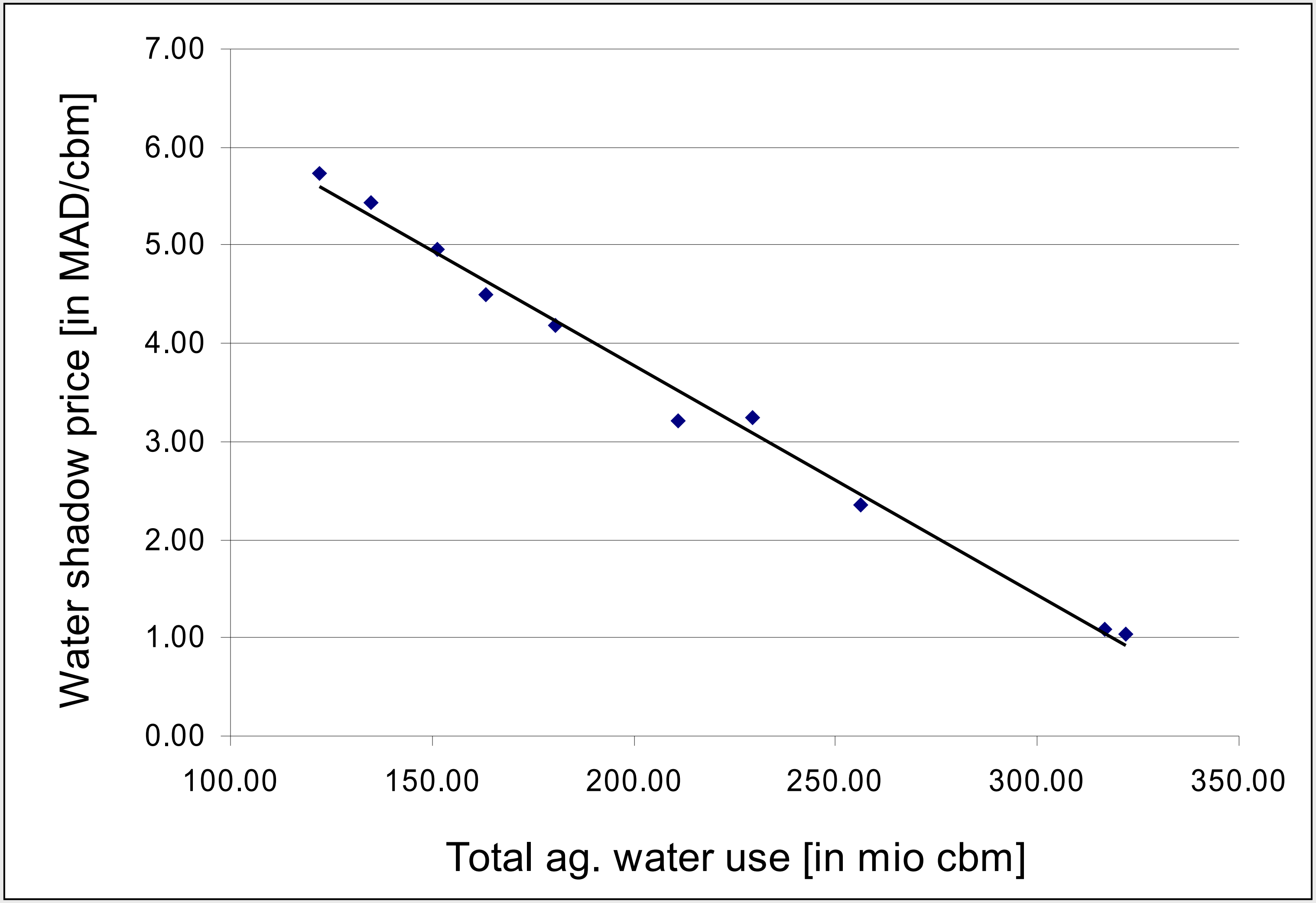
Scenarios of water pricing

General assumptions:

- Unfolding drought with a continuous reduction of surface water (-14% annually)
- Perfect knowledge of resource availability for the current year, no foresight for future years (somewhat stylised …)
- Costs of pumping groundwater: 0.58 MAD/cbm
- Surface water distribution rules across oases

1. Base run
2. 'SWC'
   => Pricing only surface water at 1 MAD/cbm
3. 'GWC'
   => Pricing only groundwater at 1 MAD/cbm (+ 0.58 pumping costs)
4. 'TWC'
   => Pricing both surface and groundwater at 1 MAD/cbm

Base run: derived demand for water



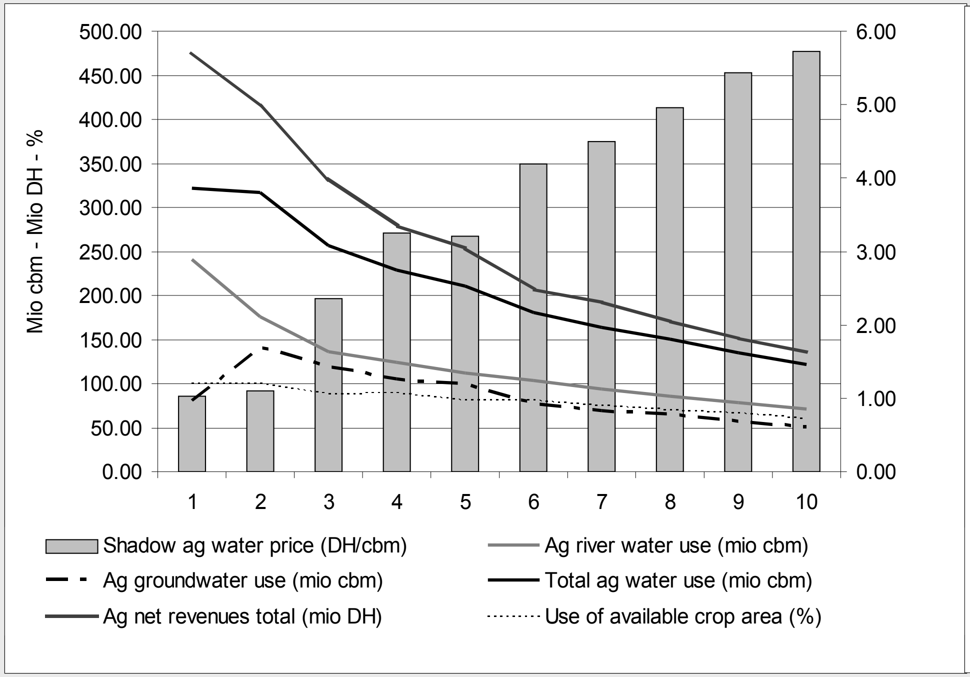
Heidecke, C., Kuhn, A., Klose, S. (2008)

A comparison of scenarios

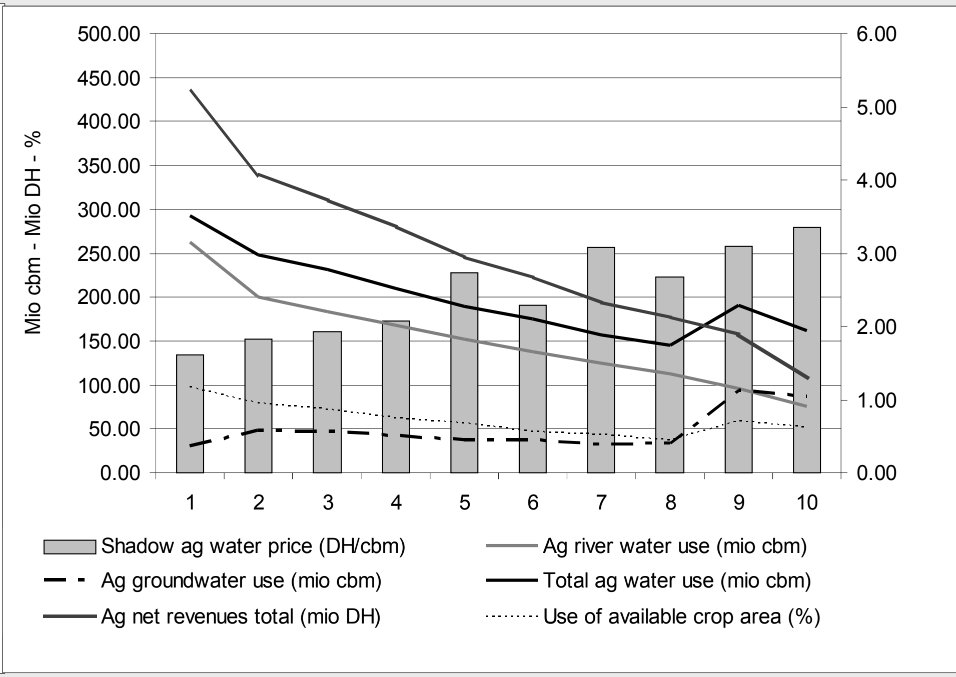
	Base run	SWC	GWC	TWC
Agric. river water use (mio cbm)	123.0	117.0	151.0	137.0
Agric. groundwater use (mio cbm)	86.0	92.9	49.4	66.3
Water shadow price (DH/cbm)	2.5	2.5	2.3	2.3
Agricultural net revenues (mio DH)	260.8	122.2	246.2	57.2
Sum of water charges (mio DH)	0.0	117.4	49.2	206.3
Total basin revenues (mio DH)	260.8	239.6	295.4	263.5
Agricult. net revenues (disc. at 10 %)	196.0	93.7	183.1	45.6
Total basin revenues (disc. at 10 %)	207.3	189.9	214.6	194.9

Overview on results over ten years

Base run



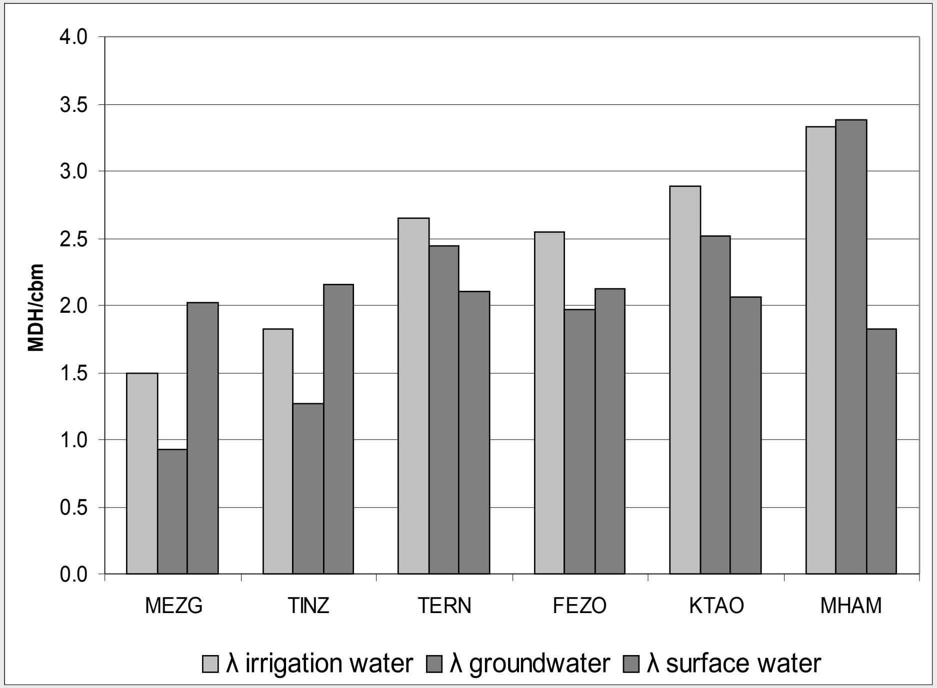
Groundwater pricing



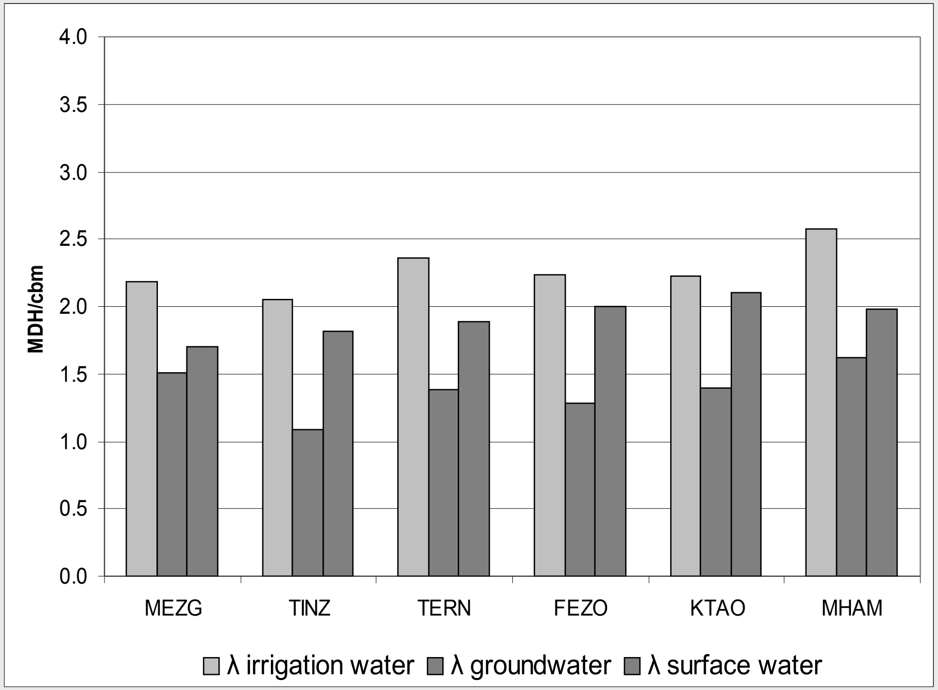
More even distribution of water scarcity across years
Under pricing, bulk of groundwater use during the last two years

Water shadow prices in oases, ten-year averages

Base run

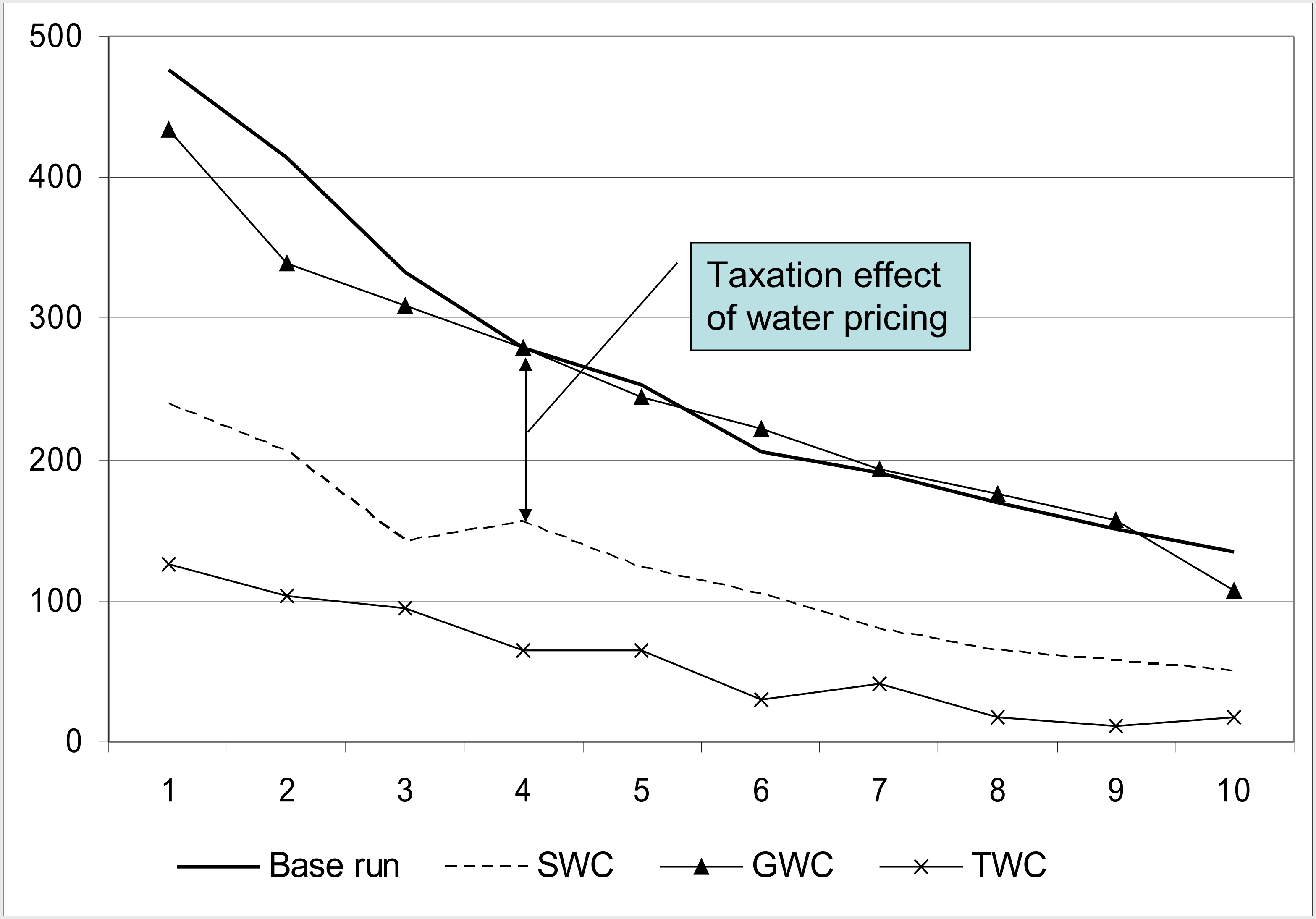


Groundwater pricing

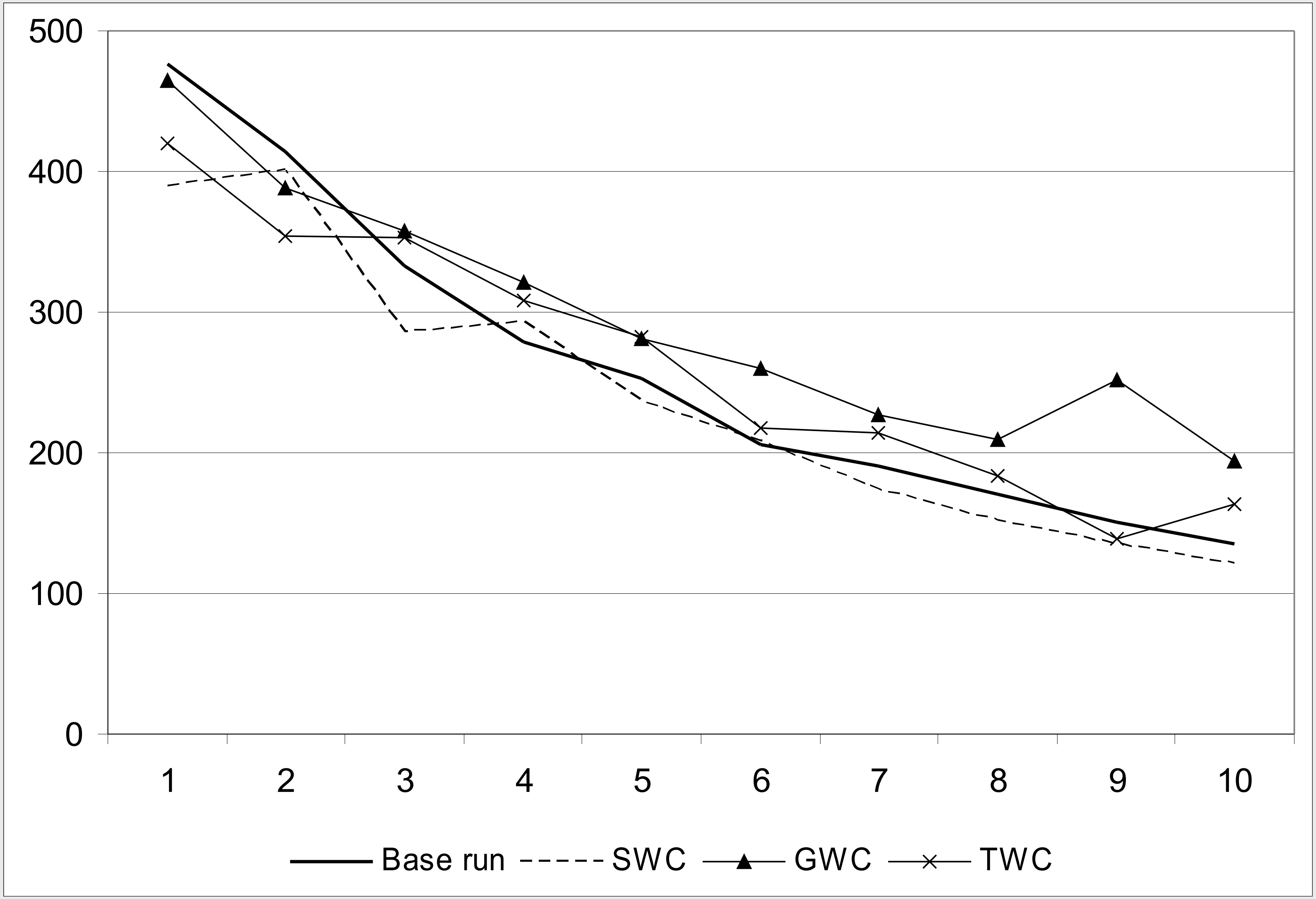


More even distribution of water scarcity across locations

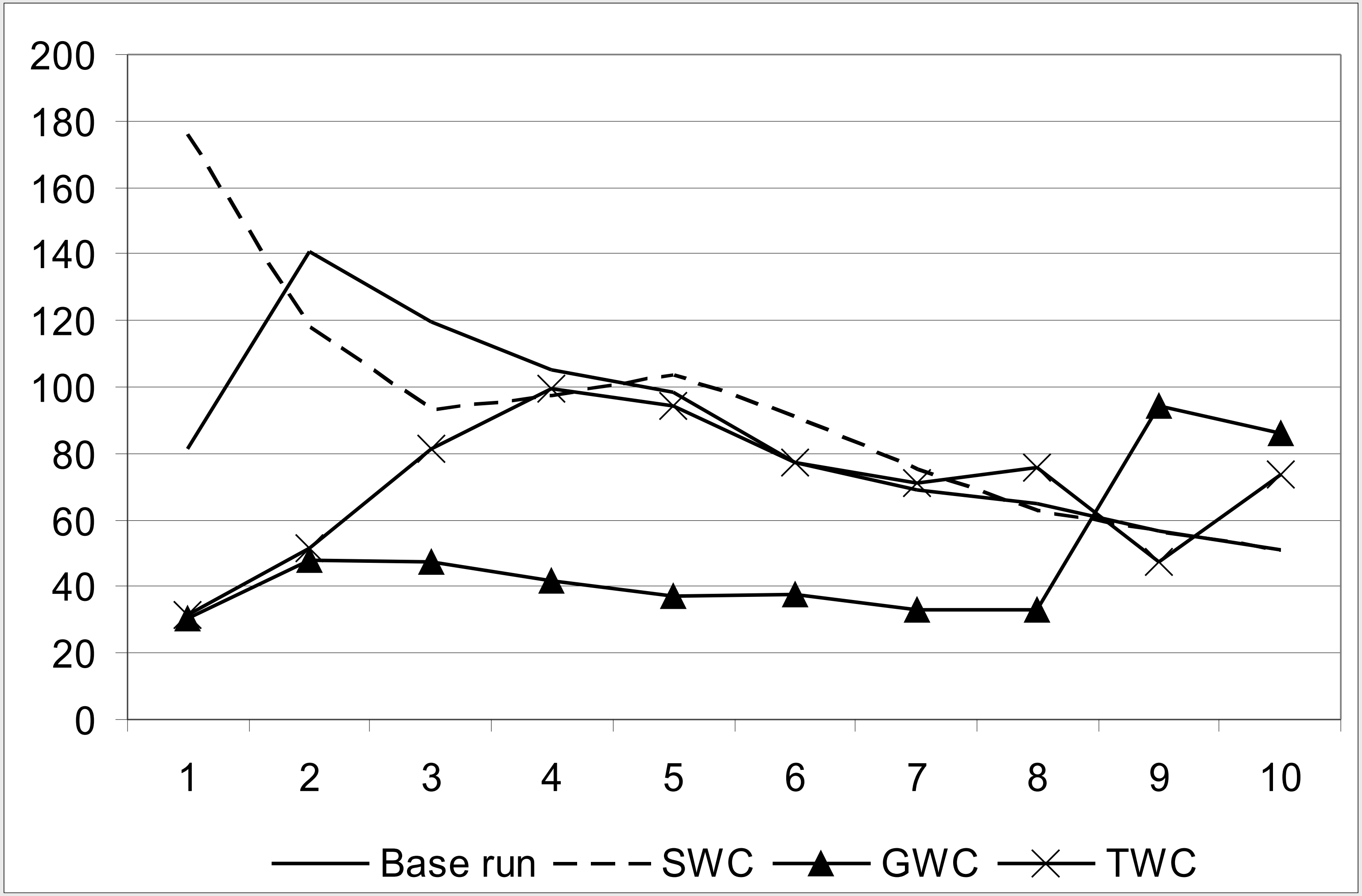
Net agricultural revenues over time (Mio DH)



Net basin revenues (incl. water charges)



Groundwater use in different scenarios



Conclusions

- Groundwater pricing seems worth considering:
  - incomes are stabilised
  - groundwater resources are preserved
  - the buffer value (in-situ) of groundwater stocks is used
  - the taxation of farmers is comparably mild
  - it may even increase basin-wide revenues
- Groundwater quantity and quality may improve => positive external effects
- Results demonstrate attractiveness of aquifers as buffers
- Pricing of surface water aggravates groundwater mining

Caveats

- Long drought period assumed too long
- Quality differences between surface and groundwater
- Concrete implementation and its costs?
- No preservation goals regarding the river

Questions of implementation

- Political feasibility
  - Interference with local customs
  - Structural change cannot be avoided completely
  - Economic benefits may not be worth the political price
  - Ministries divided over water pricing in the Drâa basin
  - Should charges for water use be compensated?
- Costs of implementation and compensation
  - Monitoring individual use vs status of the local aquifer?
  - Rule out private pumping to ease monitoring?
  - Should charges finance investments?
- Transaction costs
  - New administrative structures needed?
  - Communal or individual liability for overuse of water?

Outlook

- Compare recursive-dynamic to fully dynamic model
- Stochastic simulations
- Identify buffer value of reservoirs and aquifers
- Endogenous water pricing
- Comparison of pricing and water markets
- Better representation of external effects
- Consideration of implementation costs

Acknowledgements

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Additional information

Documentation:

http://www.ilr1.uni-bonn.de/agpo/rsrch/impetus/doc/mivad-docu.pdf

Website IMPETUS Morocco at ILR:

http://www.ilr1.uni-bonn.de/agpo/rsrch/impetus/impetus_e.htm