Combining the best of two worlds - An integrative water modelling approach

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Abstract

This paper presents a generic and flexible modelling approach combining a water focused computable general equilibrium model (STAGE_W) with a non-linear mathematical programming model for the water sector (MYWAS). The advantage of this setup is that it allows to consider economy-wide effects of changes in the water sector, while considering topography and infrastructural limitations of water supply which affect regional provision costs. Further our approach considers a flexible set of different water qualities. The two models are linked by exchanging changes of result variable vectors in an iterative process. We apply our approach to study the case of the water-energy-food nexus in Israel. A large share of the potable water consumption in Israel stems from desalination and wastewater recycling. Although both activities are considered as viable means to reduce pressure on the already overused aquifers, they are highly energy intensive and thus expansive. Recently, three large gas fields have been discovered in the Mediterranean Sea close to the Israeli coast. Their exploitation is expected to considerably decrease domestic energy prices. This in turn will make the production of energy-intensive commodities including desalinated and recycled water cheaper. The economy wide effects of this shock are analyzed in this paper.

Keywords: water-energy-food nexus, Israel, water sector model, CGE model

1. Introduction

Water scarcity is an increasing problem in many regions of the world. Already in the year 2000, 1.6 billion people were living under severe water-stressed conditions, a figure which is expected to reach 3.9 billion by 2050 which would be more than 40% of the world's population (OECD, 2012). It is estimated that in the same period global freshwater demand will increase by 55% due to a growing global population and increasing economic wealth, leading to higher demand for water as well as water-intensive products.(OECD, 2012). The quantity of water available for usage is limited however and mostly determined by precipitation. With continuing climate change rainfall patterns are predicted to become more erratic whereas due to rising temperatures, evaporation rates are expected to increase in many parts of the world, resulting in a reduced and more unsteady supply of freshwater predominantly in regions which already suffer from water scarcity today (Collins et al., 2013).

These opposing trends result in many cases an unsustainable overexploitation of water resources. An increased use of alternative water sources such as desalination of seawater and reclamation of wastewater is often considered as a possible mitigation strategy, however producing water from these sources is energy-intensive. On the consumption side the agricultural sector accounts for about 70% of global water withdrawals. Therefore in order to sustainable manage the water sector one needs to look at it from a cross-sectoral perspective. The concept of the water-energy-food nexus has been applied in this respect to describe the complex and inter-related nature of the global resource system (FAO, 2014).

Computable General Equilibrium (CGE) models have been proven useful to analyze economy wide effects of changes in such complex and interlinked systems, as they allow depicting the direct and indirect reciprocal linkages between all economic activities and agents within and economy. Therefore this type of models has been increasingly used in recent years to analyze water related problems However, economy-wide models are often quite aggregated, and lack the spatial resolution needed to account for the profound variability in water quality and supply costs. Also infrastructural capacities and hydrological conditions might pose regionally differentiated limits to water supply. Yet, CGE models depicting the water economy usually assume a countrywide unified supply price and a completely integrated water supply network which allows the conveyance of any water quantity from A to B.

Hydro-economic modeling poses an alternative approach, which is commonly used for the analysis of water management policies (Harou et al., 2009). For that purpose, highly detailed water sector models are utilized, which are capable of including regional detail and constraints as well as the water supply topology as existent. However, these models only provide a rather crude picture of the demand side as well as the rest of the economy (e.g. neglecting substitution effects on different levels, changes in welfare, trade, etc.). Therefore, in this paper an integrative water modelling approach is developed in order to combine the strengths of both approaches while overcoming their complementing weaknesses.

2. Previous Approaches

Similar approaches of linking CGE and single sector models have been applied to other research fields such as the analysis of biofuel policies (Britz & Hertel, 2011). However, there are only few previous studies which focus on the water sector. Robinson & Guneau (2013) combine a dynamic CGE model with a regional water system model to analyze the impacts of changes in water resources in the Indus rivers basin. Yet, this application is limited to surface water and agricultural water use only. Baum et al. (2016) link a CGE model of the Israeli economy to a farm-level model to empirical estimate substitution elasticities of different water qualities. Also this application is focused on the water consumption by the agricultural sector and provides no regional differentiation.

The approach presented here goes beyond those previous applications. Our model also incorporates different water qualities (e.g. potable water, desalinated water, recycled wastewater and brackish water) such as in Baum et al. (2016) and which can be flexibly adjusted. Specific water activities (e.g. groundwater pumping, desalination, wastewater recycling) produces these water qualities using different specific water resources (e.g. groundwater, seawater, and wastewater). Thereby the quantity of wastewater available is linked to the potable water consumption of municipalities. Also we include different household groups in order to determine distributional effects. Moreover by incorporating a detailed and dynamic water sector model, our approach allows to determine specific water provision costs at different localities and for the endogenous expansion of water related infrastructure.

3. STAGE_W-MYWAS modelling framework

The approach presented in this paper is based on the integration of STAGE_W, a water focused CGE model (Luckmann & McDonald, 2014) with MYWAS a non-linear mathematical programming (NLP) model for the water sector (Fisher & Huber-Lee, 2011). The later was recently extended to allow higher flexibility in the optimization process (Reznik et al., 2014). The two models are linked by exchanging changes of result variable vectors in an iterative as shown in Figure 1 for an energy price shock: The economy-wide effects of a change in the energy price are simulated with the help of STAGE_W. Resulting changes in the electricity price as well as in water demand are fed into MYWAS. MYWAS in turn is used to calculate the specific regional supply costs of the demanded different water commodities (i.e. potable water from groundwater or desalination, reclaimed wastewater, brackish water) considering topography and possible restrictions of infrastructure. The change in total water supply costs as well as in regional (efficient) water prices are fed back to STAGE_W, which is solved again in order to determine the demand shifts induced by the new water supply prices. The updated demand quantity is fed back to MYWAS, which endogenously allows the expansion of local water supply infrastructure if required. As this again influences water provision costs, this procedure is iterated minimizing changes in water supply prices and demand quantities.

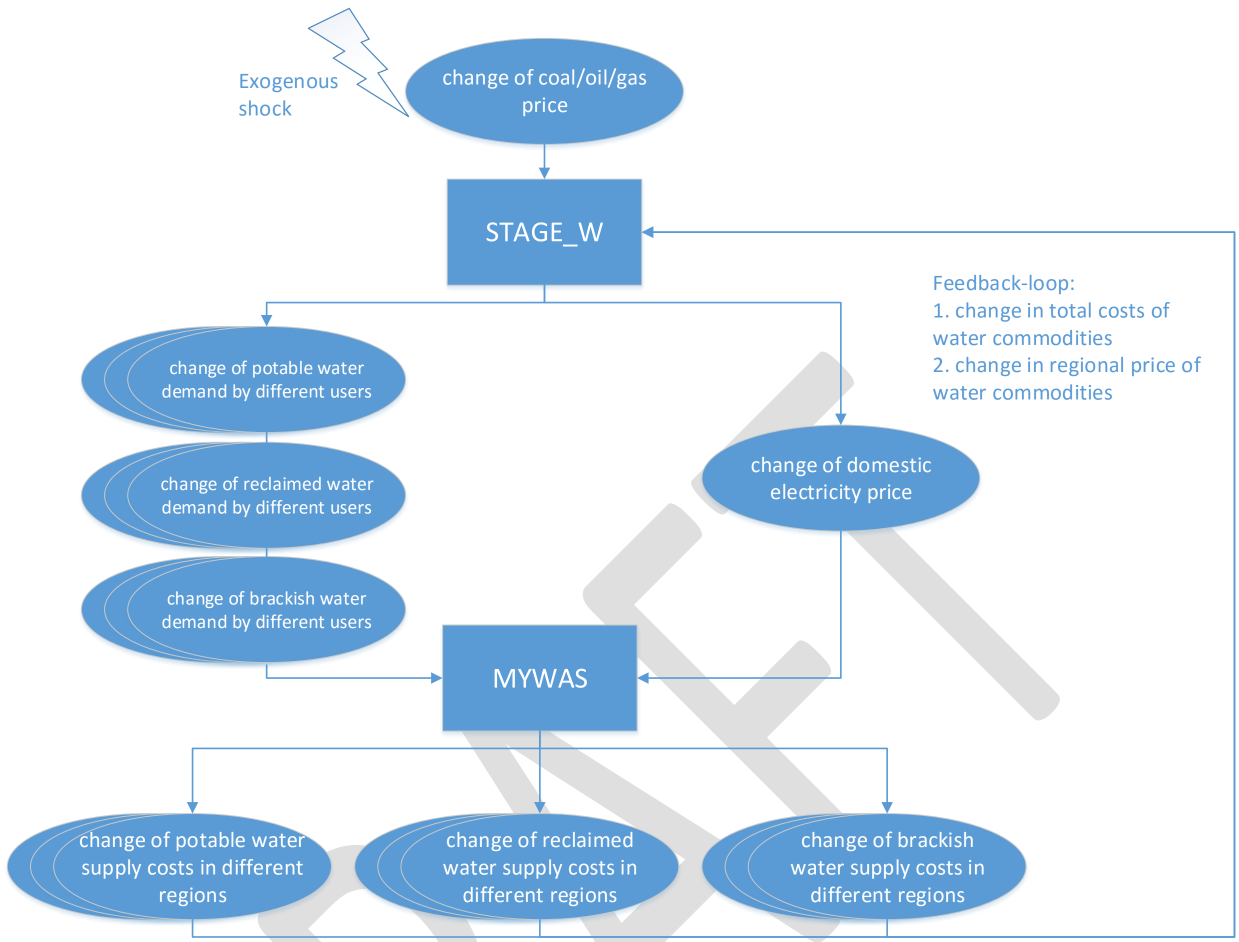

Figure 1: STAGE_W-MYWAS modelling framework, interlinkages of an energy-price shock.

4. Case study

We demonstrate our approach by applying it to the case of the water-energy-nexus in Israel. A large share of the potable water consumption in Israel stems from desalination and wastewater recycling. Although both activities are considered as viable means to reduce pressure on the already overused aquifers, they are highly energy intensive and thus expansive. Recently, three large gas fields have been discovered in the Mediterranean Sea close to the Israeli coast. Commercial exploitation started in 2013 but will be significantly expanded in 2016/17 (Siddig & Grethe, 2014). With the help of STAGE_W we analyze the effect this has on the price of energy in Israel. The results are fed into MYWAS as described in section 3.

5. Expected results and conclusions

The additional gas supply is expected to considerably reduce domestic natural gas and energy prices. This in turn will make the production of energy-intensive commodities including desalinated and recycled water cheaper. Leading to an increasing demand from water intensive activities such as irrigated agriculture, inducing an expansion of water supply infrastructure. While total production expands there are also substitution effects which might lead to a depression of factor prices. Yet total domestic production is expected to expand and the overall welfare effect on households to be positive.

The presented integrated modelling approach allows quantifying these changes and providing details regarding the required additional water infrastructure. Still, the modelling setup is generic and flexible such that it can be applied to a much wider set of scenarios studying the water-energy nexus and beyond.

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19th Annual Conference on Global Economic Analysis

Washington DC, USA

June 15-17, 2016

Rationale

- Complementarity of General Equilibrium and Single Sector Models:
  - CGE-Models: economy-wide linkages and indirect effects
  - Single sector models: high resolution, (spatial) detail
- Water
  - Economy wide integration
  - Regionally differentiated supply/demand, infrastructural capacities

Previous Approaches

- Robinson & Guneau (2013)
  - dynamic CGE model with + regional water system model
  - analyze the impacts of changes in water resources in the Indus rivers basin
- Baum et al. (2016)
  - link a CGE model of the Israeli economy + farm-level model
  - empirical estimate substitution elasticities of different water qualities

MYWAS

- **The**

Multi-

Year

Water

Allocation

System

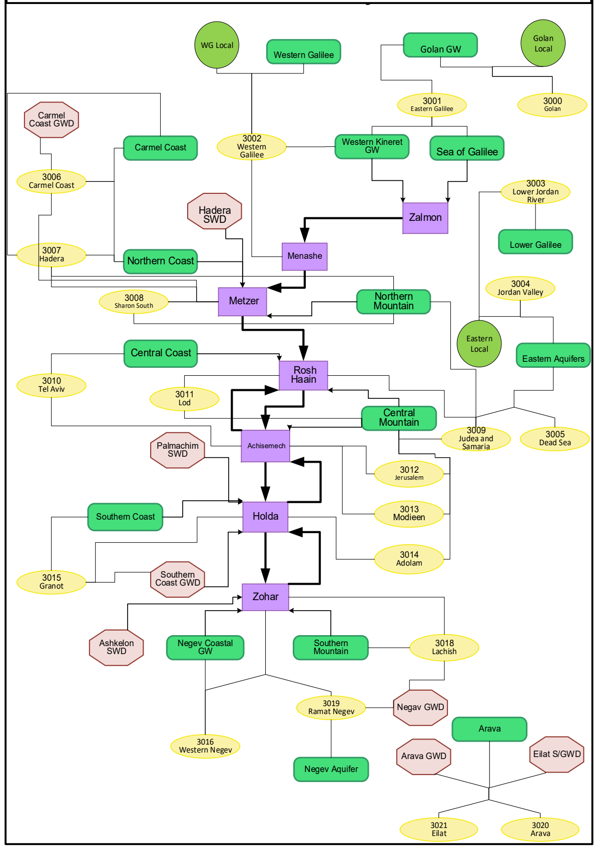
model

MYWAS

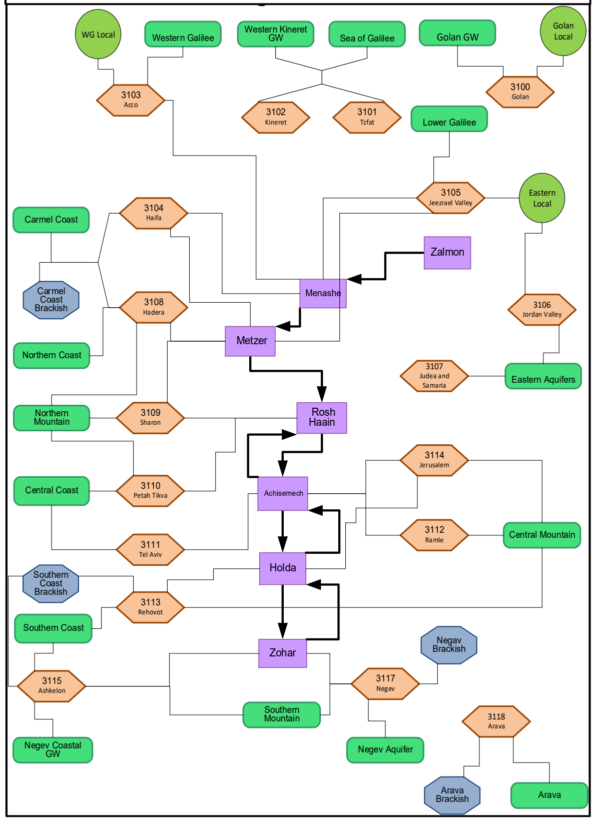
- High-resolution NLP-model of economy-wide water supply (Fisher & Huber-Lee, 2011)
- Reznik et al., 2014:
  - Topology adjustments:
    - Urban (21) and agricultural (18) consumption regions separated
    - Sources (46) differentiated from demand regions
    - Including wastewater treatment, desalination and additional conveyance infrastructure
  - Calibrated to Israeli data for 2010

Topology

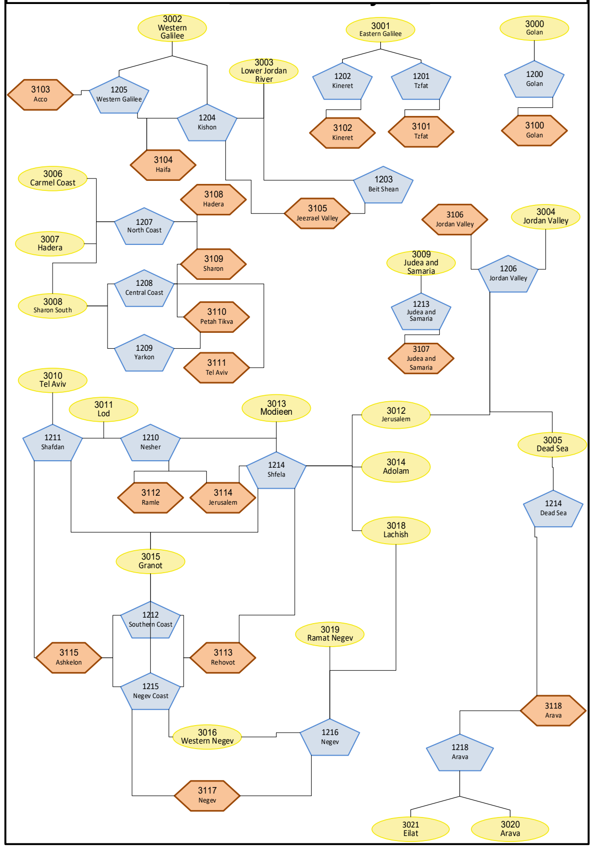
Freshwater System



Freshwater + Non-freshwater - Agriculture



Wastewater System



Demand

- Urban-sector demand

  Constant-elasticity demand functions based on Bar-Shira et al., (2005) + calibration:

  $$p_{\phi}^{u} = \upsilon \cdot \left(Q_{\phi}\right)^{\mu}$$

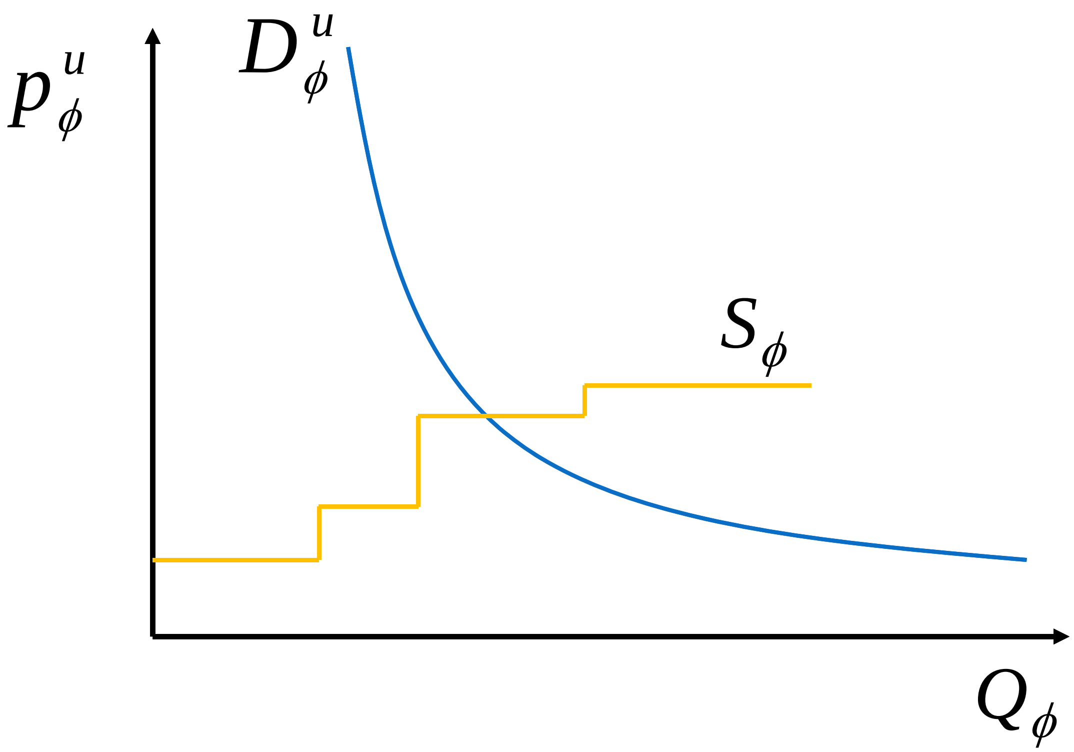
- Agricultural-sector demand

  Incorporates the substitution between freshwater, treated wastewater and brackish water

  Calibrated, using elasticity estimates (Bar-Shira et al., 2006) and administrative conversion ratios:

  $$p_{\phi}^{a} = \alpha \cdot \left(Q_{\phi} + \delta Q_{w} + \gamma Q_{\beta}\right)^{\eta}$$

Demand and Supply



Optimization

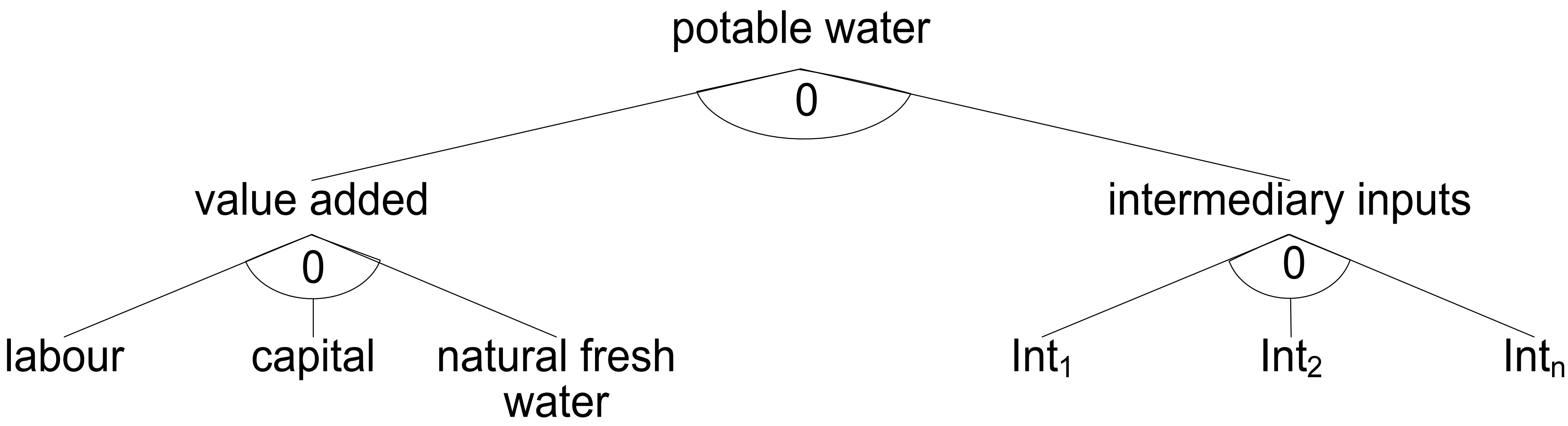
- Nationwide allocation
  - Optimal water production by sources and inter-sector water allocation
- Intra-agricultural sector allocation
  - Optimal allocation of fresh, brackish and recycled water to the various agricultural regions
- Exogenous factors
  - Costs (energy, operation, maintenance, capital), constraints (minimal stocks, sewage treatment).

STAGE_W

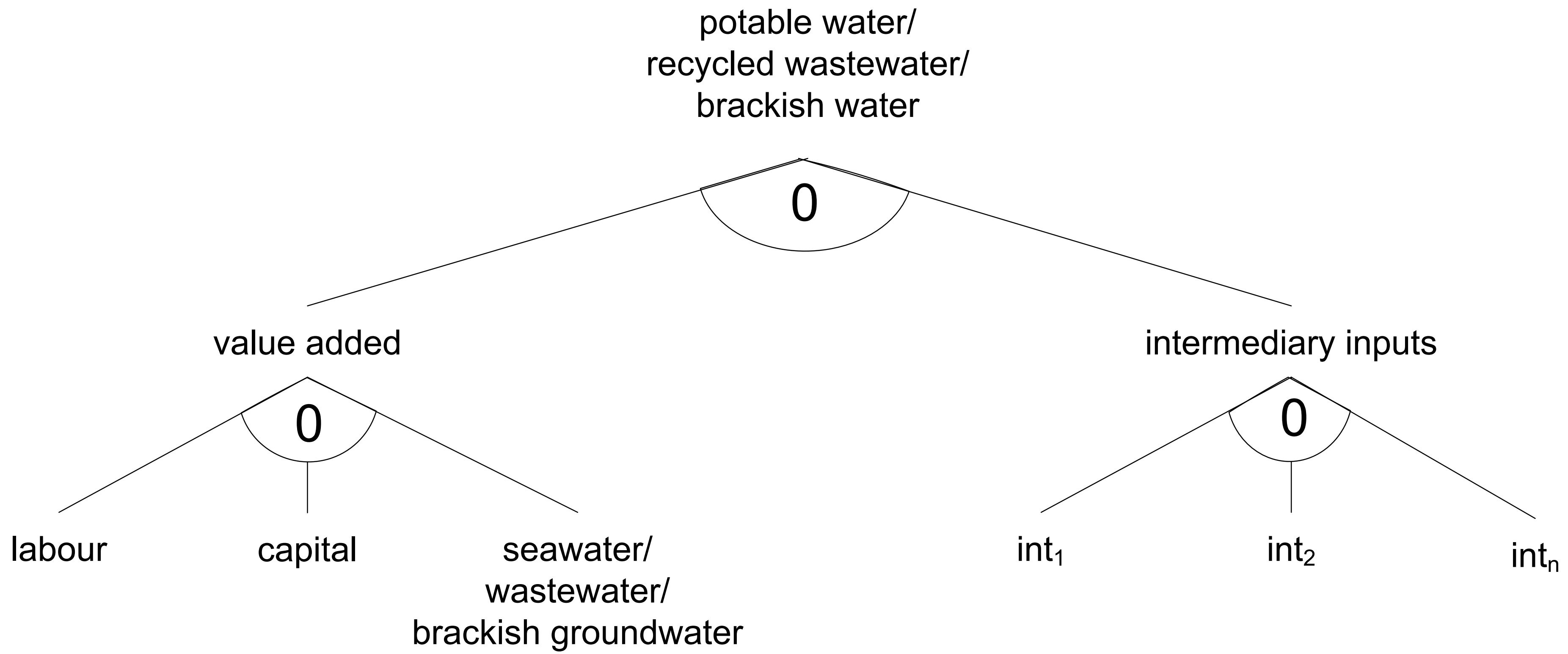
- Based on STAGE (McDonald, 2007)
  - Single country, static CGE-model
- Multiple water resources, activities and commodities
- Water taxation-instruments on
  - Activities
  - Commodities
  - Users → Price discrimination

(Luckmann & McDonald, 2014)

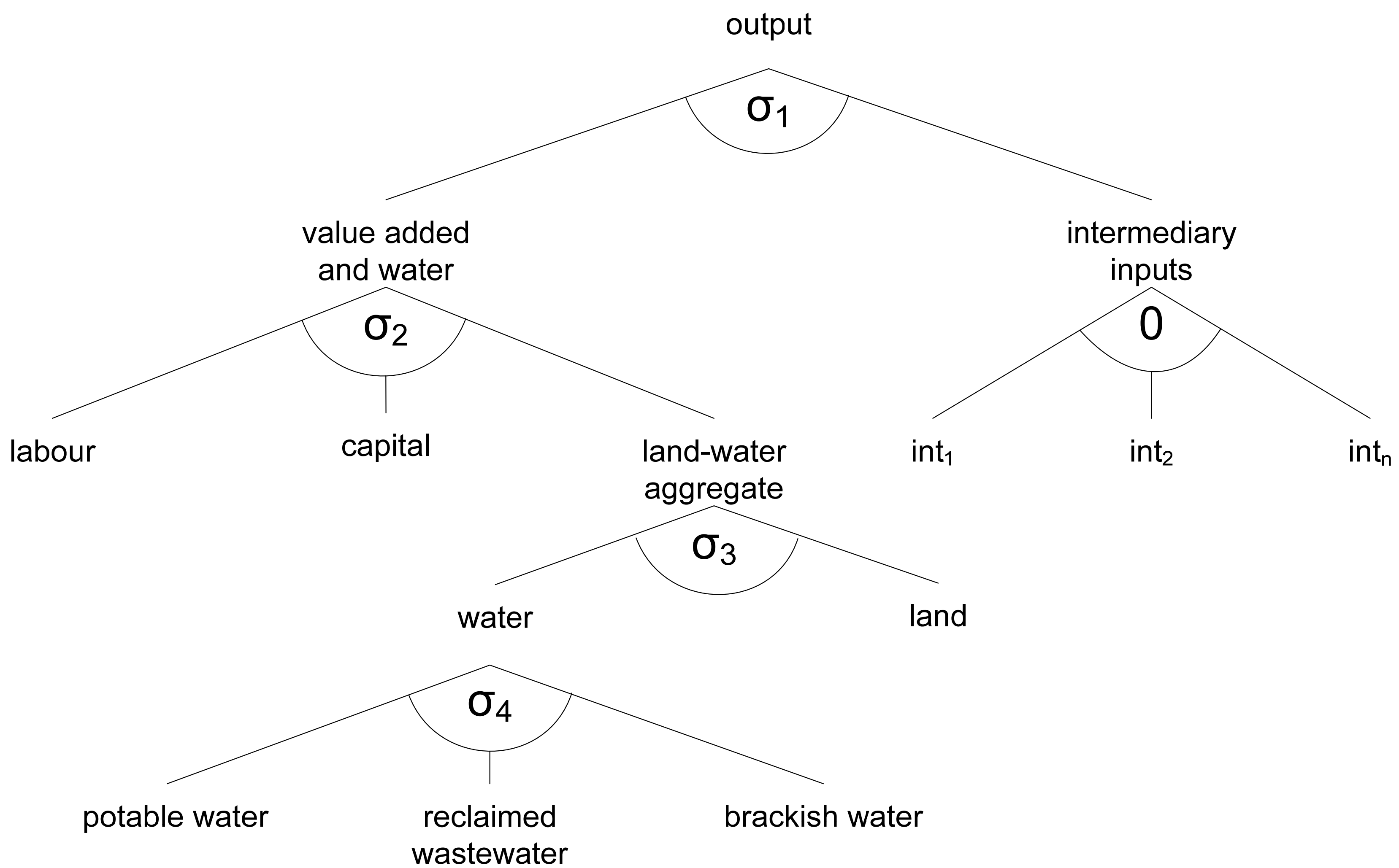
Production structure
Water commodities



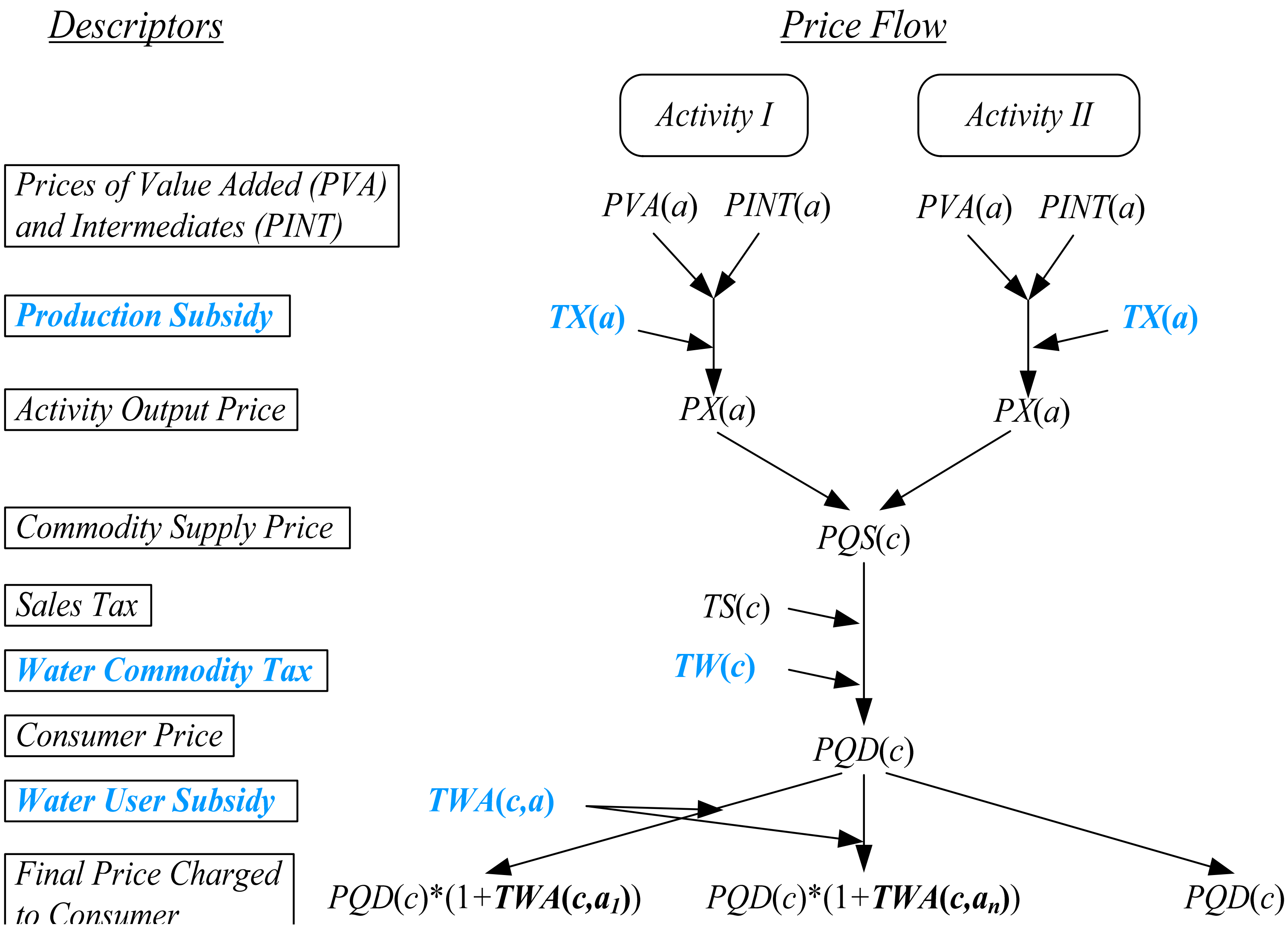
Production structure
Water commodities



Production structure
Non-water commodities



STAGE_W - Water taxation instruments



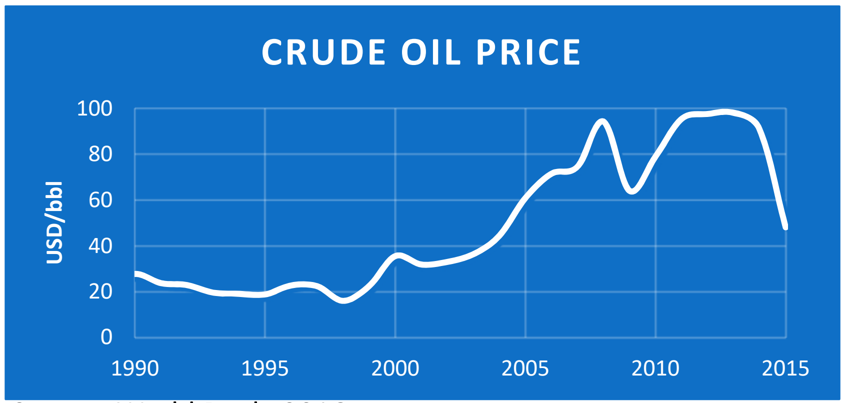
Database

- SAM based on Siddig et al. (2011)
  - Updated to depict the Israeli economy of 2010
  - 205 accounts
    - 45 activities and commodities
    - 41 factors
    - 10 household-groups

Scenarios

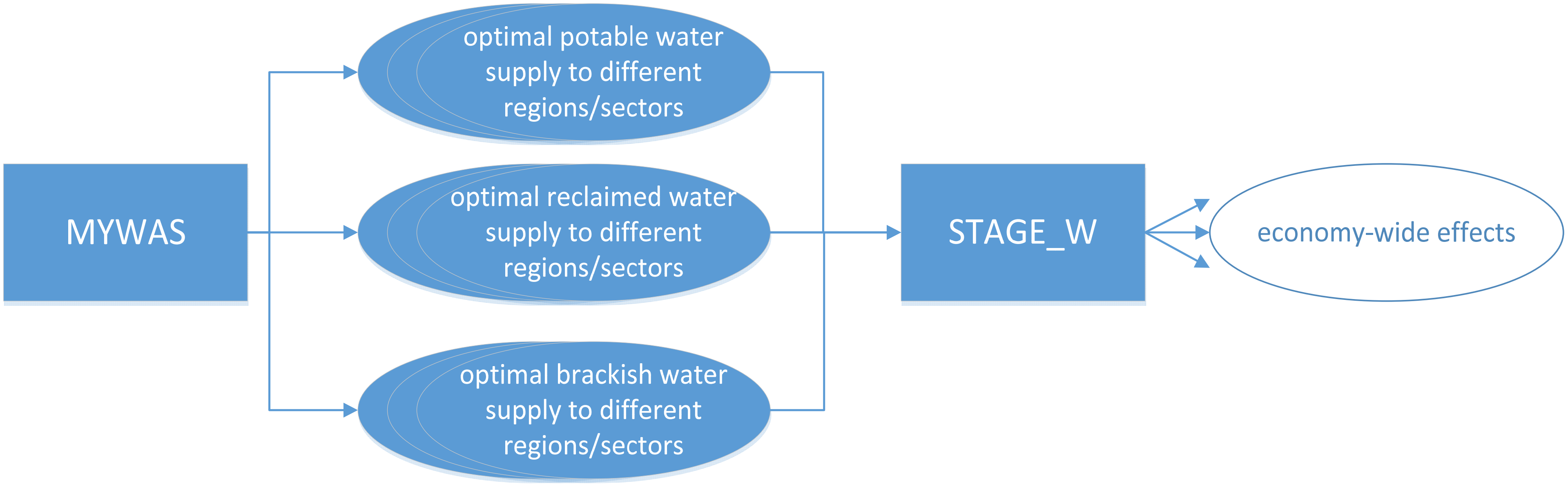
- Optimization of water supply (**Opt**)
  - Adjustment of water policy instruments
  - Keeping government deficit constant

- Additional decrease of primary energy price (**PElow**)
  - 30% reduction of import price of primary energy

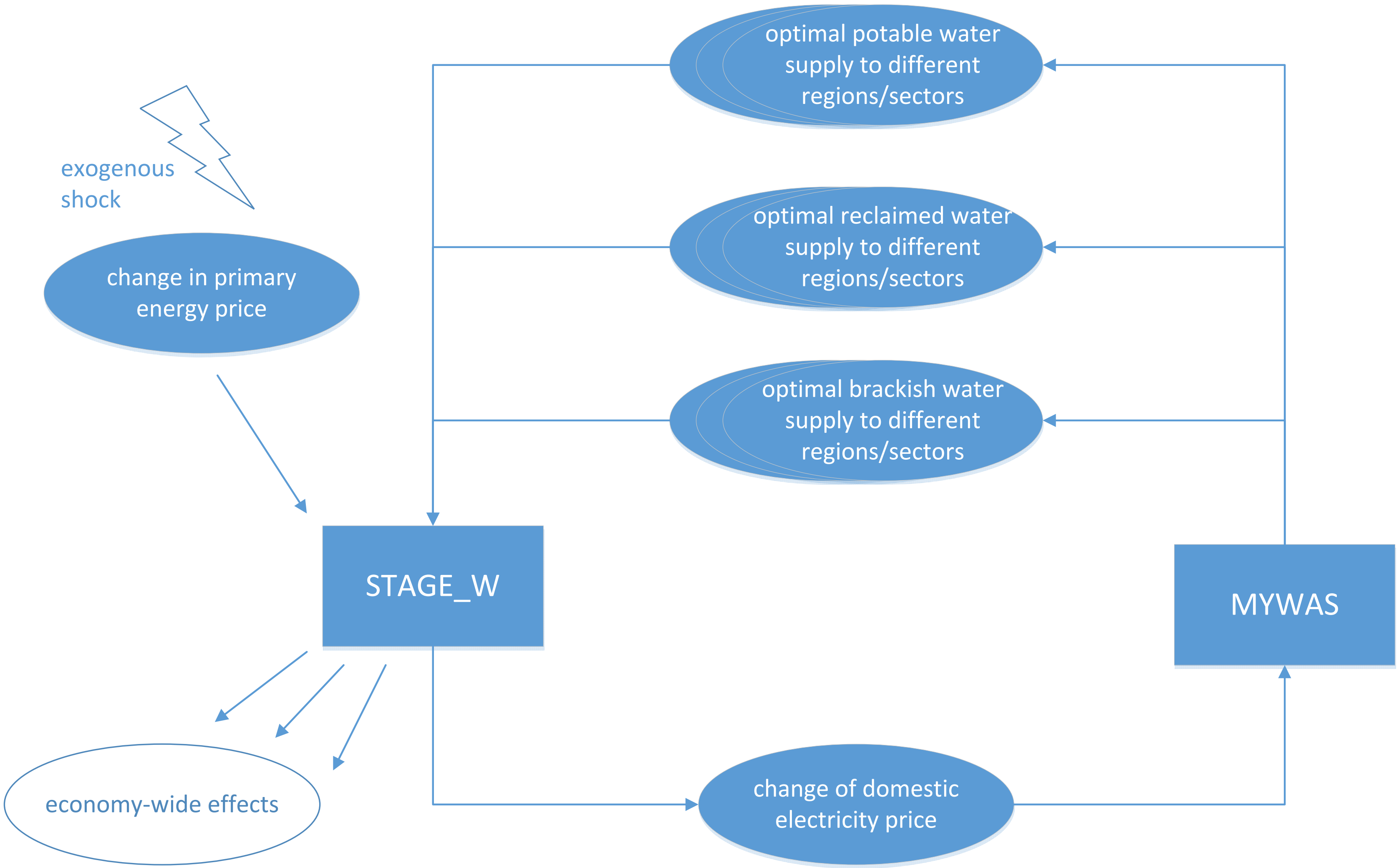


Source: World Bank, 2016

Modelling Setup
Opt-Scenario



Modelling Setup
PElow-Scenario



Closures I

- Water sector
  - Total natural freshwater water supply limited to average annual recharge rate
  - Water-supply to different sectors fixed according to MYWAS-results
  - Endogenous adjustment of water taxation instruments
  - Water factors fixed unit value, flexible quantities
    - exception: wastewater→ linked to municipal potable water consumption

Closures II

- Government
  - Fixed government deficit
  - Flexible household income tax
- Non-Water-Factors
  - Labour, capital and land fully employed and mobile
- Trade
  - World market prices fixed
  - Flexible exchange rate

Water Sources

	Base m³	Opt %-change	PElow %-change
Natural fresh water	1061	13%	13%
Brackish water aquifers	179	-46%	-46%
Desalination	313	-43%	-38%
Wastewater treatment	425	10%	11%
Total	**1978**	**-2%**	**-1%**

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Plant	Base m³	Opt %-change	PElow %-change
Hadera	145	-92%	-82%
Palmachim	45	0%	0%
Ashkelon	120	-2%	0%
Eilat	3	0%	0%
National Total	**313**	**-43%**	**-38%**

Water Sources

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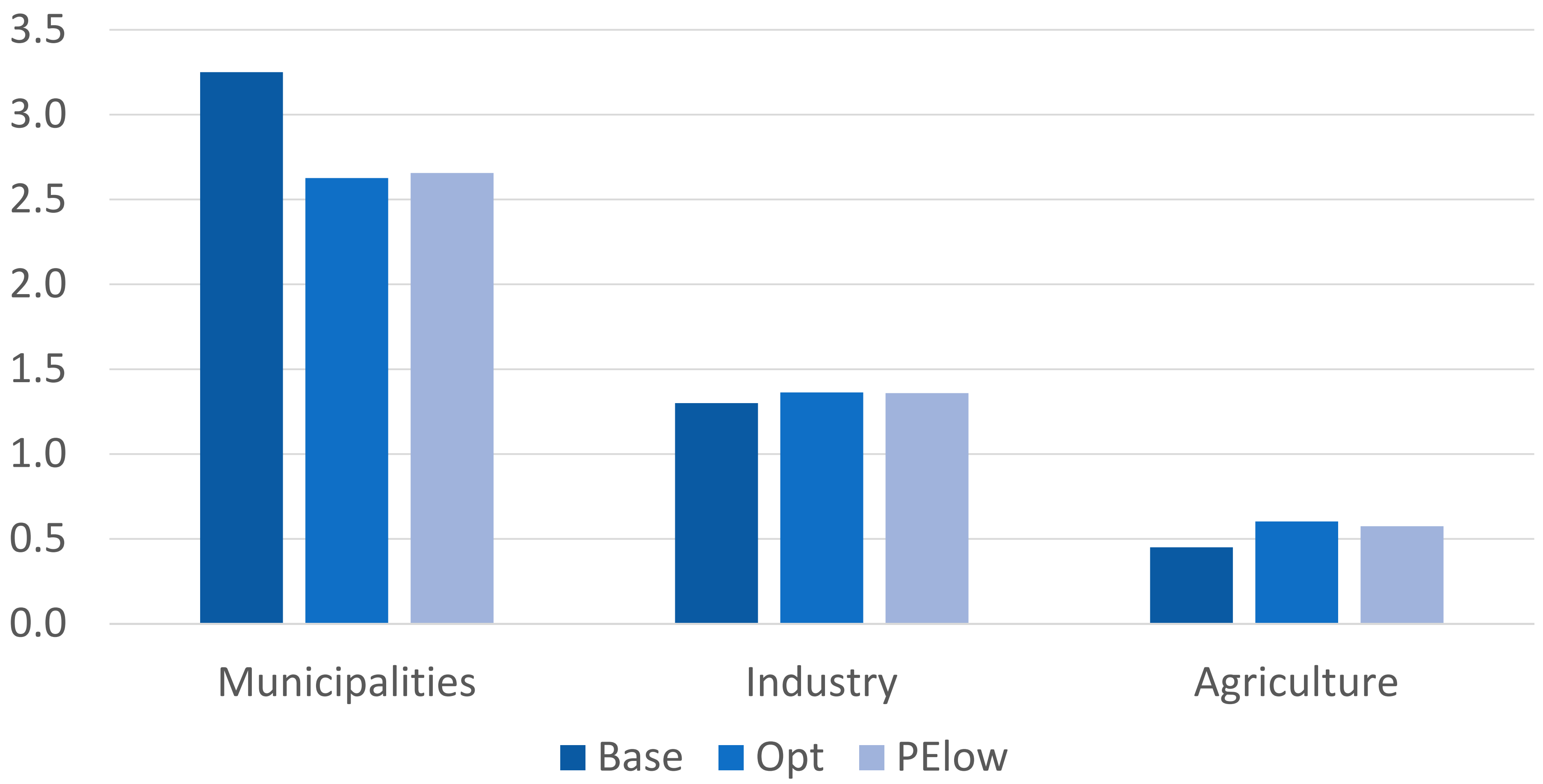
Desalination	313	-43%	-38%
Wastewater treatment	425	10%	11%
Total	**1978**	**-2%**	**-1%**

Plant	Base m³	Opt %-change	PElow
Arava	8	9%	9%
Kineret	10	0%	0%
Western Galilee	35	0%	0%
Jordan Valley	11	0%	0%
North Coast	17	11%	11%
Central Coast	37	36%	34%
Shafdan	85	11%	13%
South Coast	7	3%	3%
Kishon	43	18%	19%
Dead Sea	2	0%	0%
Negev	38	0%	0%
Golan	3	12%	12%
Tzfat	10	22%	24%
Beit Shean	3	0%	0%
JS Settlements	3	13%	8%
Nesher	22	4%	4%
Yarkon	14	-53%	-47%
Shfela	39	33%	33%
Negev Coast	38	0%	0%
National Total	**425**	**10%**	11%

Water Prices



Water Consumption

Sector	Water quality	Base m^3	Opt %-change	PElow
Municipalities	potable	752	11%	11%
Industry	potable	129	0.0%	0.3%
Agriculture	potable	493	-16.7%	-13.9%
	recycled	390	19.9%	19.9%
	brackish	179	-46.3%	-46.4%

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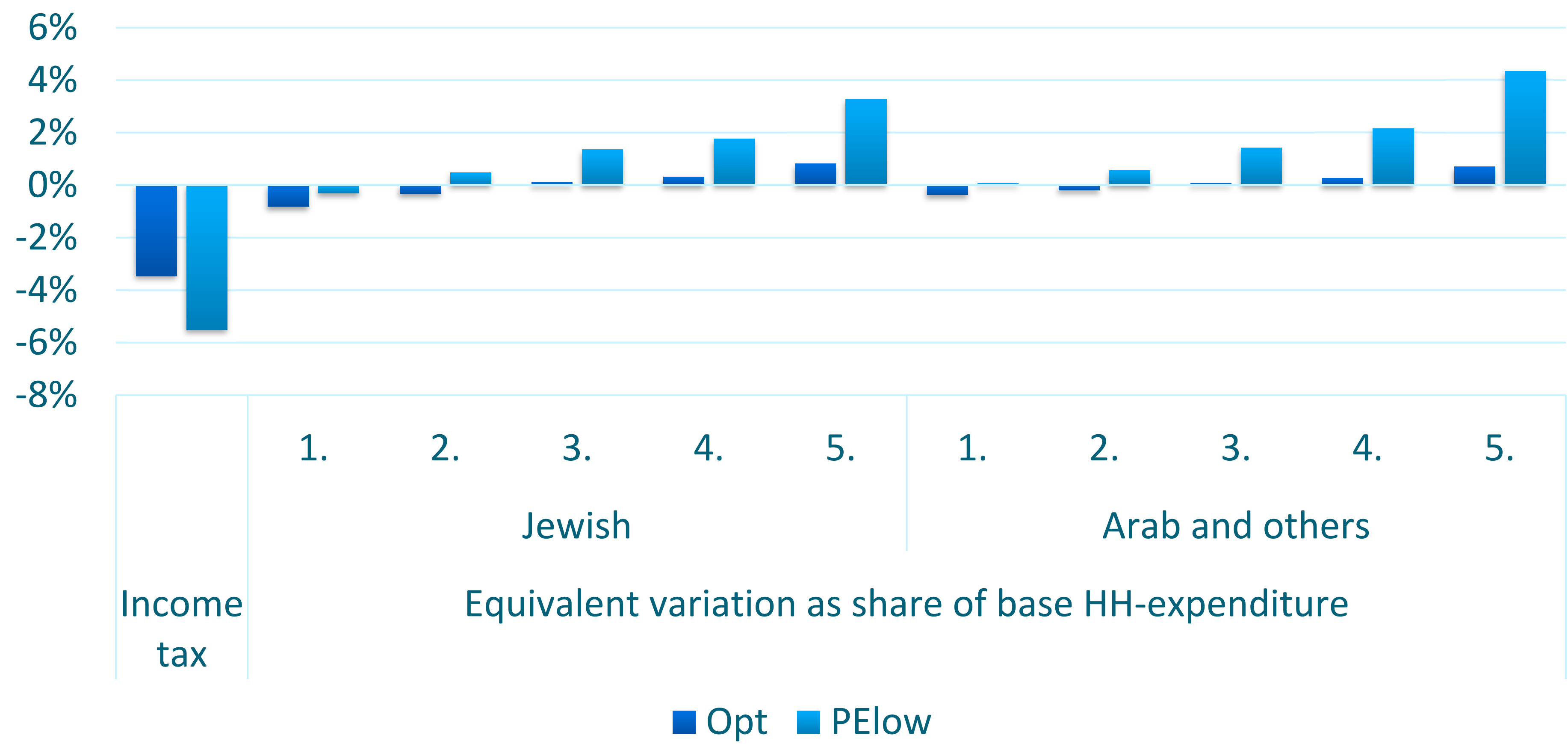
	recycled	390	19.9%	19.9%
	brackish	179	-46.3%	-46.4%

Consumption regions	Base m³	Opt %-change	PElow %-change
Sharon South	87	12%	12%
Golan	5	12%	13%
Eastern Galilee	79	12%	13%
Western Galilee	126	11%	11%
Carmel Coast	8	12%	12%
Hadera	25	12%	13%
Granot	71	12%	12%
Jordan Valley	7	13%	14%
Jerusalem	62	9%	10%
Lachish	46	11%	11%
Western Negev	28	11%	12%
Ramat Negev	5	10%	11%
Arava	3	14%	14%
Lower Jordan	7	10%	11%
Judea and Samaria	15	13%	8%
Tel Aviv	112	10%	10%
Lod Lowland	37	11%	12%
Modieen	15	11%	11%
Adolam	1	10%	11%
Dead Sea	6	9%	9%
Eilat	7	11%	11%
National Total	**752**	**11%**	**11%**

Macro-Results

	Opt	PElow
real GDP	+0.12%	+0.21%
Supply	+0.05%	+0.89%
Absorption	+0.12%	+1.02%
Imports	+0.05%	+2.33%
Exports	+0.06%	+0.26%

Households


6%
4%
2%
0%
-2%
-4%
-6%
-8%
1.
2.
3.
4.
5.
1.
2.
3.
4.
5.
Jewish
Arab and others
Income tax
Equivalent variation as share of base HH-expenditure
Opt
PElow

Concluding remarks

- Flexible, generic modeling approach

  →Depicts economy-wide effects of changes in the water sector/regional water sector outcomes of exogenous shocks

  → Considers topography and infrastructural limitations of water supply

  →Internalizes non-water sector responses

  →Applicable to a wide set of scenarios, studying the water-energy nexus and beyond

Outlook

- Introduction of dynamics (infrastructure development)
- Hard-linking of models
- Transboundary water management

Thank you for your attention!

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