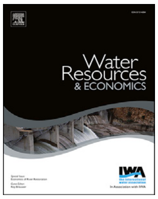
ARTICLE IN PRESS

Water Resources and Economics xxx (2017) 1–13

Contents lists available at ScienceDirect

Water Resources and Economics

journal homepage: www.elsevier.com/locate/wre



Water policy guidelines: A comprehensive approach[☆]

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ARTICLE INFO

JEL classification:
C61
Q25
Q28

Keywords:
Water economy
Intertemporal management
Scarcity
Turnpike
Most rapid approach

ABSTRACT

We study water management in the context of a prototypical water economy containing the main water sources and user sectors. A water policy consists of water allocation from each source to each user sector at each point of time as well as the capital investments needed to carry out these allocations. We show that the optimal policy brings the water capital stocks (infrastructure and equipment) to well-specified turnpike processes as rapidly as possible and evolves along these turnpikes thereafter, eventually converging to a unique steady state. Implications for water pricing, as well as for the timing and extent of recycling and desalination activities, are discussed.

1. Introduction

The rational management of a water economy requires understanding the relations between its various components. The term “water economy” refers to a collection of water sources and user sectors that are entwined via physical (equipment, infrastructure) and social (institutions, norms, laws) capital. Water economies vary in both respects and their idiosyncratic features affect the range of feasible policies (see the examples in Refs. [1,2]). We study the salient features of water management in the context of a prototypical water economy, consisting of the main water sources and user sectors. Without committing to a particular setting, we characterize the optimal water policy in terms of intertemporal water allocations from each source to any user sector and the investments in (physical) capital needed to carry out these allocations.

We find that the optimal policy proceeds along two stages: a most-rapid-approach (MRAP) stage followed by a turnpike (singular) stage. In the first stage, the capital stocks (equipment, infrastructure) are driven as rapidly as possible (i.e., at the maximal feasible rate) to well-specified turnpike trajectories. During the second stage, the capital stocks evolve at a more moderate rate along their turnpikes, eventually converging to a steady state. The duration of the MRAP stage is inversely related to the (overall) investment budget and can be made arbitrarily short. Thus, most of the process evolution takes place along the turnpikes and specifying the optimal water policy, therefore, involves mainly specifying the turnpike policy. This simplifies the water management task considerably, as the turnpike policy includes only the water stock as a state variable but not the capital stocks.

[☆] Helpful comments and discussions by Ariel Dinar are gratefully acknowledged.

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http://dx.doi.org/10.1016/j.wre.2018.01.005
Received 27 September 2017; Received in revised form 30 January 2018; Accepted 31 January 2018

Please cite this article in press as: Y. Tsur, A. Zemel, Water policy guidelines: A comprehensive approach, Water Resources and Economics (2017), http://dx.doi.org/10.1016/j.wre.2018.01.005

The primary source of water is nature (rainfall, lakes, stream flows, aquifers). In regions where the (sustainable) supply of natural water suffices to meet human and environment needs, water is not scarce and managing it may not be high on the priority list. Such regions decrease in number over time due to demographic and climatic trends. In many populated regions, water scarcity has become critical (see Ref. [3]), stressing the need for proper management.

Two sources of produced water can be added to natural sources: recycling and desalination. Recycled water is the outcome of collecting and treating domestic and industrial sewage. As such, its supply is determined by the allocation of water to these sectors. Sewage treatment is required primarily due to health and environmental considerations, disregarding whether the treated water is reused later on. The level of treatment (secondary, tertiary) determines the range of feasible uses of the recycled water. These considerations bear important implications for the allocation of water in general as well as for the level of treatment and who should pay for the different stages of the recycling process. The model developed herein accounts for these considerations by deriving additional terms to the water prices that implement the social optimum: sewage emitters (households and industry) should pay for the direct treatment cost, but should also benefit from their contribution to the pool of recycled water, which in turn reduces the demand for natural water and the ensuing scarcity rent.

Desalinization is, for all practical purposes, an unlimited source of water, hence can be considered as a backstop technology. However, at the current state of technology, it is an expensive source. This raises the issues of when to begin desalination (if at all) and the extent of desalination over time. The answer, again, depends on the relative magnitudes of the relevant price components. When water from the other sources abound, the reduction in water scarcity may not justify large investment in expensive desalination plants.

The present effort builds on [4] framework and extends it in a number of ways. While [4] simplified the dynamic aspects by considering steady states, the water policy characterized herein is fully intertemporal, covering both the water allocation from each source to each user sector at each point of time and the capital investment (equipments, infrastructure) needed to carry out these allocations.

The next section specifies the stylized water economy that will serve as a basis for the analysis and defines feasible water policies in this economy. The optimal policy is shown, in Section 3, to evolve along the two aforementioned stages and to eventually converge to a unique steady state. Section 4 concludes and an appendix contains technical details and proofs.

2. The water economy

The water economy specified in Ref. [4] provides a convenient starting point. Water is derived from three main sources and is allocated to four main user sectors. While the primary source of water is nature (rainfall, aquifers, lakes, reservoirs, stream flows), water can be derived also from recycling facilities and from desalination plants. The four main user sectors are domestic (residential), agriculture (irrigators), industry and the environment.[1] We use the index $i = n, r, d,$ to denote natural (n), recycling (r) and desalination (d) sources, and the index $j = D, A, I, E,$ to signify domestic (D), agriculture (A), industry (I) and environment (E) sectors.

We denote by $q_{ij}(t)$ the supply flow (say, million cubic meter per year) from source i to sector j in year t. When specifying the total annual water supply from source i (regardless of the user sector) we replace the index j by the generic symbol "∘". Thus,

$$q_{i\circ}(t) = \sum_{j=A,D,I,E} q_{ij}(t),\ i = n, d, r. \tag{2.1a}$$

Similarly, the total annual allocation to sector j (regardless of the source) is

$$q_{\circ j}(t) = \sum_{i=n,r,d} q_{ij}(t),\ j = D, A, I, E. \tag{2.1b}$$

Water sources

We discuss the three water sources in turn.

Natural: Natural water is mostly derived from a finite, replenishable stock $Q(t) \in [0, \overline{Q}]$, which evolves over time according to

$$\dot{Q}(t) = R(Q(t)) - q_{n\circ}(t), \tag{2.2}$$

where $R(\cdot)$ is a decreasing and concave recharge function and the upper bound $\overline{Q}$ satisfies $R(\overline{Q}) = 0$.[2] The lower bound

$$Q(t) \geq 0 \tag{2.3}$$

implies that the supply of natural water cannot exceed $R(0)$ when $Q(t) = 0$ (the zero lower bound is a standard normalization). The capital (infrastructure, equipment) needed to allocate (pump, treat, convey, distribute) natural water is denoted K_n.

Recycled water: Recycled water is derived from treated domestic and industrial sewage. Let $q_{s\circ}(t)$ denote the flow of domestic and

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[1] Focusing on water scarce regions, we ignore hydropower and navigation sectors.

[2] Allowing for multiple natural stocks, each with its own recharge process, is outlined in Ref. [8]. If irrigation and environmental water contribute to the recharge of underlying aquifers, the recharge function takes the form $R(Q, q_{\circ A}, q_{\circ E})$, where R decreases in Q and increases in both $q_{\circ A}$ and $q_{\circ E}$. In the interest of simplicity, the latter effects are ignored.