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Working Paper

Efficient Management of Water Quality

Volkswirtschaftliche Diskussionsbeiträge, No. 47-94

Provided in Cooperation with:

Fakultät III: Wirtschaftswissenschaften, Wirtschaftsinformatik und Wirtschaftsrecht, Universität Siegen

Suggested Citation: Pethig, Rüdiger (1994) : Efficient Management of Water Quality, Volkswirtschaftliche Diskussionsbeiträge, No. 47-94, Universität Siegen, Fakultät III, Wirtschaftswissenschaften, Wirtschaftsinformatik und Wirtschaftsrecht, Siegen

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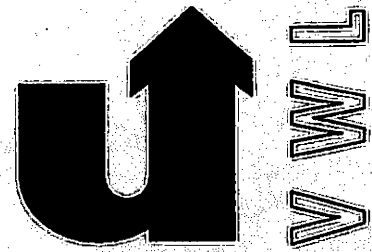
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**VOLKSWIRTSCHAFTLICHE
DISKUSSIONSBEITRÄGE**



**EFFICIENT MANAGEMENT OF
WATER QUALITY**

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University of Siegen

DISCUSSION PAPER NO. 47-94

**UNIVERSITÄT - GESAMTHOCHSCHULE - SIEGEN
FACHBEREICH WIRTSCHAFTSWISSENSCHAFTEN**

Abstract

In its first part, the paper focuses on the relationships between the quality of the water resource, industrial sewage, and waste water treatment in two successive steps: intra-industrial waste abatement followed by centralized end-of-pipe purification in (public) purification plants. Purification plants are viewed as firms producing water quality with both conventional inputs and with the water resource's assimilative capacity. In a two-commodity two-factor general equilibrium model various second-best policy regimes are studied which implement politically predetermined water quality standards. Water quality management turns out to become *inefficient* by requiring to finance purification through the revenue from industrial sewage charges.

Next a two-region model is studied where a 'sewage charge' on industrial pollution is levied along with an effluent charge on the residual waste content of the water released by the purification plant into a recipient water resource. Purification plants are required to balance their budgets and/or the revenues from effluent charges are earmarked for subsidizing wastewater treatment processes. Various institutional arrangements are scrutinized with respect to their (in)efficiency implications.

In the last part of the paper a general equilibrium model is developed in which drinking water is produced from raw water with the help of labor whose productivity increases with raw water quality. Raw water quality is assumed to depend on both the size of the water protection area and on that amount of assimilative services of the raw water resource which is not used for waste assimilation. The central question is whether efficiency requires the price of drinking water to equal its marginal production costs in the water works or whether high quality raw water from water protection areas is a scarce resource in the sense that it carries an economic rent.

Raw water turns out to be always scarce if industrial pollution does not spill over at all into the water protection area. Otherwise, if in the initial situation raw water is abundant, then it becomes less abundant — and possibly eventually scarce — with increasing demand for drinking water, with increasing labor endowment and with decreasing land endowment.

EFFICIENT MANAGEMENT OF WATER QUALITY

by Rüdiger Pethig, University of Siegen

1. Introduction

Some decades ago, water management used to be the exclusive domain of public administrators, lawyers and engineers. But in the 1960's, in the dawn of environmental economics as a discipline, some U.S. economists like Kneese (1964) and others spoke up and argued convincingly that water management was an important economic issue dealing with scarcity, (shadow) prices and (in)efficient allocation of resources. Since these pioneering days the relevance of the economic dimension of water management is widely acknowledged, and environmental economics is beginning to have some practical impact on real world water management. But in most countries, economic concepts of cost effectiveness and incentives related to prices, fees or charges have been adopted only partially and very reluctantly. Commands and controls are still pervasive in legislation and management.

The present paper reinforces the environmental-economic perspective of water quality management that had emerged some thirty years ago. On the basis of more recent insights in modeling environment-economy interdependencies, it applies simple general equilibrium models focusing on non-priced (natural) factors of production, on displacement effects of incorrect pricing and on the allocative consequences of inadequate institutional arrangements in water management. Rather than attempting to review the large literature on water management since the days of Kneese (1964) the aim is to provide an integrated and extended analysis of water management as developed, in particular, in Pethig (1988, 1989a, 1989b, 1994) and in Pethig & Fiedler (1989, 1991/92).

Even though water resources have to be managed with respect to both their quantity and quality this paper is essentially restricted to the analysis of water quality management, dealing with water quantity management only in the context of the provision of drinking water which constitutes an important interface of the management of water quality and water quantity. Throughout the paper a general equilibrium framework is applied in order to capture the main effects and feedbacks of ecological-economic interdependence.

It is not intended to embark on an intertemporal analysis of modeling the ecological dynamics resulting from the relative size of emissions and assimilative capacity. Rather, a long-term perspective is adopted of choosing among alternative ecological stationary states which are characterized by those pairs of emission flows and water qualities that can be sustained in the long run. In this context nature's 'assimilation technology' will turn out to be decisive, a relationship, which associates emission flows to steady state water qualities and hence determines the 'technology' of producing water quality.

Section 2 focuses on the basic relationships between the quality of the water resource, industrial sewage, and waste water treatment in two successive steps: intra-industrial waste abatement followed by centralized end-of-pipe purification in (public) purification plants. Consideration of this two-stage waste water treatment process is empirically important, because many firms are so-called 'indirect dischargers' leading their waste to central purification facilities through the sewerage. Purification plants are conventionally viewed as using productive factors to produce 'waste reduction'. Without any substantive change in the basic technological and ecological hypotheses we suggest to consider, instead, purification plants as firms producing water quality with both human inputs and with the water resource's assimilative capacity.

The analysis of Section 2 is carried out in a two-commodity two-factor general equilibrium model with intra-industrial waste abatement and centralized end-of-pipe purification. As a first step a complete set of partly fictitious competitive markets is constructed yielding efficient prices for using the water resource both as waste receptor and as a 'consumption good'. This perfect 'market solution' serves as a benchmark for a comparative institutional analysis of water quality management. Second-best policy regimes are studied which aim to implement politically predetermined water quality standards. The first strategy under scrutiny is to maintain the competitive market for assimilative services as in the perfect market solution combined with cost-minimizing production of water quality. The second one consists in imposing an industrial sewage charge and requiring the purification plant to obey a self-financing constraint in the sense of matching the plant's operating costs with the revenues from the industrial sewage charge. The allocative implications of these second best policy regimes are modeled and compared. Water quality management turns out to become *inefficient* by requiring to finance purification through the revenue from industrial sewage charges. It is shown, moreover, that industrial waste abatement is too low, and the wastewater treatment facility operates at an inefficiently high level.

Section 3 continues to investigate the two-stage purification process with

intra-industrial waste abatement followed by centralized end-of-pipe purification. As in the last part of Section 2 the goal is to implement a predetermined water quality standard by pricing the use of assimilative services (called sewage charge). But in addition an effluent charge is now levied on the purification plant for the residual waste content of the purified water which it releases into the recipient water resource. Such a charge resembles the German wastewater charge (Abwasserabgabe) which imposes duties on direct dischargers.¹

The model set up in Section 2 is applied in Section 3 to scrutinize the joint impact of sewage and effluent charges under different institutional arrangements: Purification plants may be required to observe a zero-surplus (or cost-covering) requirement and/or it may be required by law that the revenues from effluent charges are earmarked in the sense that their proceeds have to be spent for subsidizing wastewater treatment processes.² For the case of earmarked effluent charges the analysis has to be extended to a two-region model.

If no effluent charge is levied and the regional purification plants are cost minimizers without being required to obey a cost-revenue constraint then the overall allocation of resources turn out to be efficient relative to predetermined water quality standards. An earmarked effluent charge levied on at least one of the regional purification plants amounts to a lump-sum monetary transfers for the purification plants not affecting at all the resource allocation in the absence of cost-revenue constraints. In other words, if an efficient water quality management is pursued, based on sewage charges only, then the additional implementation of effluent charges – whether earmarked or not – neither detracts from nor improves upon allocative efficiency and hence need not be introduced in the first place.

The results are different and more complex, however, if the regional purification plants are subject to zero-surplus constraints. We know from Section 2 that in the absence of effluent charges, purification plants will operate at an inefficiently high level while the associated industrial waste abatement activities will be too low. It turns out that implementing non-earmarked effluent charges reduces this type of inefficiency. In fact,

¹ When introduced in 1976, this charge was broadly welcomed by economists as a breakthrough in applying well-founded efficiency-oriented economic reasoning (Rat von Sachverständigen für Umweltfragen 1974, p.12). It had also been recommended to be implemented in the United States (Brown and Johnson 1982).

² This view may be rejected on the grounds that charging the purification plant for "producing" water quality amounts to accepting the 'pollutees-pay-principle'. But note that the market economy is not characterized by the polluters-pay- or the pollutees-pay-principle but by the 'users-pay-principle'. See also Pethig (1989a).

there is a tuple of positive regional effluent charges that restore efficiency. Observe, however, that these favorable effects of effluent charges should not be taken as a basis for recommending those charges, since they simply 'correct' the 'policy failure' of zero-surplus constraints rather than correcting a 'market failure'.

The next step in Section 3 is to assume that the proceeds of the effluent charge are earmarked for purification, e.g. an effluent charge is levied on region 1's purification plant while the effluent charge revenue is redirected as a subsidy to the purification plant of region 2. In this case allocative efficiency increases in region 1 and decreases in region 2. If region 2 was already less efficient than region 1 in the zero-effluent charge situation, any positive effluent charge leads to a global net efficiency loss. Otherwise, the overall efficiency will slightly improve for low rates of the effluent charge but will be impaired if the effluent charge exceeds some positive threshold value.

Water resources are used in various ways, and for many of these uses the quantity of water is important along with water quality. A case in point is the provision of drinking water calling for a combined water quantity and quality management. In many countries drinking water has to be generated from polluted raw water taken from water protection areas. Therefore a conflict concerning raw water quality arises because the water works incur increasing costs for cleaning polluted raw water while the polluters from industry and/or agriculture would have to bear additional costs if they were forced to reduce the emission of pollutants.

This issue is addressed in Section 4. To keep the analysis tractable we assume that water pollution outside of water protection areas is so severe that raw water used for the generation of drinking water must exclusively be taken from these areas. Their size not only defines an upper bound for the amount of drinking water supply, but it also influences the quality of raw water; the larger is the body of water in that area, the higher is its quality resulting from *given* pollution spillovers. Moreover, we are not concerned with water scarcity in (semi) arid zones but rather think of European countries like Germany in which water is not scarce if its quantity is considered irrespective of its quality. Then the central question is whether efficiency requires the price of drinking water to equal its marginal production costs in the water works or whether high quality raw water from water protection areas is a scarce resource in the sense that it carries — or should carry — an economic rent (Brösse 1980). If raw water should turn out to be scarce, efficiency would require to set the price of drinking water above marginal production cost.

Conceptually, the quality of drinking water can be improved by raising the "purification effort" at any of the following three margins: (i) the reduction of raw water pollution by decreasing the flow of pollutants altogether; (ii) the increase of purification efforts in the water works; (iii) the extension of water protection areas, thus diminishing the effects of pollution spillovers from outside the protected area. These three activities form the process of raw water purification in a broader sense. Efficiency of this process requires equalizing the purification effort at all three margins. Placed in that perspective, the demonstration of raw water scarcity requires the size of water protection areas to be a binding constraint for the supply of drinking water in an efficient allocation.

Section 4 develops a general equilibrium model in which drinking water is produced from raw water with the help of labor whose productivity increases with raw water quality. Raw water quality is assumed to depend on both the size of the water protection area and on that amount of assimilative services of the raw water resource which is not used for waste assimilation.

The first basic but straightforward result is robust to different specifications of the "production technology" of raw water quality: raw water turns out to be always scarce if industrial and/or agricultural pollution does not spill over at all into the water protection area. If this rent were ignored in the process of price formation of drinking water, one would expect water protection areas to be excessively (or inefficiently) large. Since, however, the complete absence of pollution spillovers is of limited empirical relevance, we proceed by assuming that pollution spillovers do occur.

In this case one can show that if the production function of raw water quality is linear homogeneous and the initial situation is a competitive equilibrium (with a complete set of – partly fictitious – markets for labor, land, assimilative services, raw water, raw water quality, drinking water, and the consumption good) in which raw water is abundant, then raw water becomes less abundant – and possibly eventually scarce – with increasing demand for drinking water, with increasing labor endowment ('economic growth') and with decreasing land endowment. It is possible to identify specific conditions on endowments, technologies and preferences under which the efficient price of raw water is, in fact, positive.

On the other hand, if the production function of raw water quality is assumed to be homogeneous of degree zero, the efficient allocation cannot be decentralized by (shadow) prices, i.e. no general competitive equilibrium exists. To obtain further insights, raw water quality is assumed to be managed by a public enterprise that supplies raw water quality efficiently and free of charge. The implications of this model with respect to the

scarcity of raw water are similar as those under the assumption of linear homogeneous raw water quality production. In particular, for similar restrictions on production functions, conditions are identified under which raw water carries an economic rent or is abundant.

2. Sewage Charges, Self Financing, and Efficiency

First we construct a simple aggregate general equilibrium model of an economy with a complete set of – partly fictitious – markets generating efficient prices for the competing uses of the water resource both as a waste receptor and as a 'consumption good' (Lindahl procedure). For the purification plant two different concepts of cost covering or self-financing will be distinguished:

- (i) In the full-scale market solution, the plant receives revenues from selling the water quality to the consumers. Its costs encompass conventional operating costs and the payment for its use of assimilative services of the water resource. The difference between those revenues and costs is denoted **revenue-cost difference I**, for short: RCD I.
- (ii) In the conventional perspective, the expenditure on the industry's use of assimilative services, the industrial sewage charge, is viewed as the purification plant's revenue, and it is considered relevant to look at the difference between this revenue and the plant's operating cost. We refer to this difference as the **revenue-cost difference II**, for short: RCD II.

With a complete set of markets RCD I is easily identified as the purification sector's profit which is clearly non-negative in competitive equilibrium under the assumption of convex production technologies, whereas the revenue-cost indicator RCD II turns out to be completely meaningless in the full-scale market solution. Looking at the purification plant as a producer of water quality clarifies that requiring $RCD II = 0$ is, in fact, a very strange political constraint: industry is an ordinary neoclassical price taker on all markets, but the second sector, consisting of the public sewage purification activity, provides its output "water resource quality" free, receives one of its inputs, namely assimilative services of the water resource, costlessly, and is asked to adjust its operating cost to the revenue from an industrial sewage charge. Having placed the issue in this perspective, the main result of Section 2 comes as no surprise: *in general, water quality management becomes inefficient by imposing the cost-covering constraint $RCD II = 0$ on purification. It is shown, moreover, that the associated industrial waste abatement activity is too low, whereas the wastewater treatment facility operates on an inefficiently*

high level. The RCD $\Pi = 0$ rule is bound to be wasteful, because it implies divergent (implicit) evaluations for different uses of assimilative services.

Section 2.1 develops the basic building blocks of the model. Section 2.2 serves to present the Lindahl solution to efficient water quality management. It is imagined that a private 'water resource owner' seeks to maximize, as a price taker, the return on his or her asset by charging positive prices for *all* uses of the water resource. Acknowledging the impossibility of such a venture, Section 2.3 presupposes the government to implement some political water quality standard and analyses the allocative efficiency under different institutional arrangements. The main attention is drawn on the trade-off between the minimum cost implementation of water quality and the cost covering requirement RCD $\Pi = 0$ in the public purification plant. The inefficiency of the self-financing strategy is characterized.

2.1 The Model

Consider an economy whose **industrial sector** produces two outputs: a consumption good Y (with quantity y) and industrial waste as an undesired joint product. Labor (quantity ℓ), the industry's only conventional productive factor, can be used both for the production of the consumption good and for intra-industrial waste abatement. Denote by e_y , with the letter 'e' for **emission**, the amount of waste (i) that is produced but not abated within industry, (ii) that is discharged by the industry into the sewerage and (iii) that is treated 'at the end of the pipe' in an (aggregate) wastewater treatment facility, called the '**purification plant**'. The production of the consumption good along with intra-industrial waste abatement or avoidance is modeled by the concave production function $Y: D_y \rightarrow \mathbb{R}_+$, where

$$(1) \quad y = Y(\underset{+}{e_y}, \underset{+}{\ell_y}),$$

$Y(0, 0) = 0$, and $D_y := \{(e_y, \ell_y) \in \mathbb{R}_+^2 \mid \ell_y \geq \bar{s}e_y, \bar{s} > 0\}$. Observe that the emission e_y is treated in (1) as an input, even though we deal with an undesired joint output. We think of e_y as the industry's demand for a productive factor, namely for **waste assimilation services** of the water resource.

Consumers derive utility from the consumption good Y and from the quality of the water resource Q (with quality indicator q), or the **water quality**. Utility is positively related to water quality, because there are various (offstream) consumptive uses of the

water resource. The satisfaction from all these uses is assumed to rise with increasing water quality. Suppose, for convenience of exposition, that all consumers are identical. The representative consumer's preferences are given by a quasi-concave utility function U , satisfying

$$(2) \quad u = U(q, y). \\ + +$$

To describe the 'productive activity' of the purification plant it is necessary, as a first step, to specify how industrial waste emitted ultimately affects the quality of the water resource. In its qualitative aspects the water resource is a renewable natural resource similar as forests and fish populations are in their quantitative dimensions. More specifically,

$$\frac{dq}{dt} := \dot{q}_t = \hat{Q}(x_t) \quad \text{with} \quad \hat{Q}_x < 0 \quad \text{and} \quad \hat{Q}(0) = 0$$

is the change of water quality at time t in response to the **excess demand of assimilative services**

$$x_t := e_{yt} - V(\ell_q) - A(b_q, q_t)$$

The functions V and A are explained as follows: The purification plant uses productive resources (say, labor), ℓ_q , to neutralize industrial waste emissions. The associated production activity is described by the concave production function V where $V(\ell_q)$ is the 'waste reduced' with labor input ℓ_q . Moreover, $A(b_q, q_t)$ is nature's **assimilative capacity** depending on the prevailing water quality q_t and on the size b_q of the water resource, as measured, e.g. by the resource's geographical extension. We drop that variable b_q for the analysis in the next two sections, but reintroduce it in Section 4. The proper functional form of A is much disputed in the literature (Fiedler 1994, Pethig 1988, 1994). Here we introduce the hypothesis: *There is $q_\ell < q_u$ such that function A satisfies $A(q) = 0$ for all $q \leq q_\ell$; moreover, A is strictly concave on the interval (q_ℓ, q_u) and satisfies $\max A(q) > A(q_u) \geq 0$.*

Rather than embarking on a full-scale dynamic analysis we assume that public decision makers and all economic agents are concerned only about the long-run perspective of choosing among different ecological steady states. In other words, we ignore intertemporal adjustment paths of water quality and focus, instead, on long term ecological steady states and on shifts between those states, i.e. on comparative dynamics.

This amounts to restricting the following investigation to $x_t = 0$ or to

$$(3) \quad e_y = V(\ell_q) - A(q).$$

Equation (3) is interpreted as a relationship of ecological equilibrium of the water resource derived from the ecological equation of motion for the case $(dq/dt) = 0$. Therefore (3) means that the waste flow e is 'neutralized' in each point in time by the influence of both nature's self-cleansing processes $A(q)$ and man-made cleansing $V(\ell_q)$. Moreover the domain of function A can be restricted to the subset $[q_0, q_u]$ with $q_0 = \arg \max A(q)$, because, in general, this subset is the domain of all Pareto efficient steady states, when consumers value the water quality sufficiently positive (Pethig 1994). Observe that q_0 is the water quality generated by the stationary emission flow $e_0 := E(q_0)$, i.e. by the maximum emission flow compatible with a long term ecological steady state.

With the focus on steady states and with restricting the domain of A to $[q_0, q_u]$ it is convenient to look at the purification plant as a firm producing water quality with the inputs a_q and $e_q := e_0 - V(\ell_q) - A(q)$. In order to formalize this interpretation we rewrite this last equation as $A(q) = e_0 - e_q - V(\ell_q)$ or $q = A^{-1}[e_0 - e_q - V(\ell_q)]$ and define $D_Q := \{(e_q, \ell_q) | a_q \geq 0, q \in [q_0, q_u], A(q) = e_0 - e_q - V(\ell_q)\}$ to construct the function $Q : D_Q \rightarrow \mathbb{R}_+$ satisfying

$$\Delta q = Q(e_q, \ell_q) := A^{-1}[e_0 - e_q - V(\ell_q)] - q_0$$

Hence environmental quality is determined by

$$(4) \quad q = q_0 + \Delta q = q_0 + Q(\ell_q, e_q).$$

Clearly, Q has the properties $Q(0, 0) = 0$, $Q(0, \ell_q) > 0$ for $\ell_q > 0$, and $Q(e_q, 0) > 0$ for $e_q > 0$. It is straightforward to interpret the function Q as the purification plant's production function: The plant can choose to increase q by human effort (ℓ_q) or by increasing its use of nature's assimilative services (e_q).

The model is completed by listing the resource constraints

$$(5) \quad t_0 = t_q + t_y \quad \text{for } t = \ell, e.$$

It should be emphasized that $e_o := \max A(q) = A(q_o)$, the water resource's maximum assimilative capacity, is a natural endowment rather than a policy tool as e.g. an emission standard. Hence the equation $e_o \geq e_q + e_y$ reveals, in fact, that the purification plant competes with the industry for the use of assimilative services.

The equations (1), (2), (4) and (5) turn out to constitute an 'ordinary' neoclassical two-sector general equilibrium model with the major qualification that water quality is a public good (and with the minor peculiarity of allowing for $q_o \neq 0$). As is well-known from such models there exists a (long term) transformation function $T : [q_o, q_u] \rightarrow \mathbb{R}_+$ with $y = T(q)$ defined by maximizing $Y(e_y, \ell_y)$ subject to the constraint $q_o + Q(e_o - e_y, \ell_o - \ell_y) \geq q$. Clearly, one has $y = T(q)$ if and only if

$$(6) \quad \frac{Y_e}{Y_\ell} = \frac{Q_e}{Q_\ell}.$$

The message of (6) is that efficient water quality management requires to establish a 'division of labor' between intra-industrial waste abatement or avoidance and end-of-pipe treatment by the purification plant: The marginal labor cost of waste abatement (Y_e/Y_ℓ) must be the same as the marginal labor cost of using assimilative services in the purification plant. Equation (6) serves as an efficiency check on water quality management.

2.2 Efficient but Fictitious Pricing

Assume now, the water resource is exclusively owned by a person, called the (water) resource owner, who may – but need not – be identified as the government or a public water authority. Imagine also that there are competitive markets not only for the consumption good and labor but also for both water quality and assimilative services. In such a setting we have nonnegative prices for the consumption good (price p_y), for labor (price p_ℓ), for waste assimilation services (price p_e), and for consumptive uses of the water resource (price p_q). In order to define the corresponding equilibrium, consider first the consumers' aggregate income, consisting of total labor income, $p_\ell \ell_o$ (with ℓ_o being the economy's aggregate labor endowment), and of the resource owner's total net return from his or her water resource property rights, $p_e e_o + p_q q_o$. By assuming linear homogeneous production technologies, all profits are zero at equilibrium prices. Hence aggregate income is $p_\ell \ell_o + p_e e_o + p_q q_o$ which we redefine, for analytical convenience, as

$$z := \frac{p_\ell \ell_o + p_e e_o + p_q q_o}{p_y} = \pi_{\ell y} \ell_o + \pi_{ey} e_o + \pi_{qy} q_o,$$

where $\pi_{vy} := p_v/p_y$ for $v = \ell, e, q$. The budget constraint (as an equality) is given by

$$(7) \quad z = y + \pi_{qy} q.$$

A **Lindahl equilibrium** is constituted by a price vector $(p_a^*, p_e^*, p_q^*, p_y^*)$ and by a resource allocation vector $(a_q^*, a_y^*, e_q^*, e_y^*, q^*, y^*)$ such that: the market clearing conditions (5) are satisfied; demand equals supply for both industrial output Y and water quality Q ; the production of Y and Q is profit maximizing at prevailing prices; and the consumption allocation (q, y) results from maximizing (2) subject to (7).

It is easy to see and well-known from the literature that Lindahl equilibria are Pareto efficient and hence exhibit the following properties (Pethig 1989b):

- (i) $\pi_{qy}^* = (U_q^*/U_y^*) = T_q^* > 0$ (consumption efficiency);
- (ii) Equation (6) holds and is equal to $\pi_{e\ell}^* > 0$ (production efficiency); i.e. the real price of assimilative services must be the same for all uses of assimilative services.
- (iii) The natural assets e_o and q_o yield positive returns: $\pi_{ey}^* e_o + \pi_{qy}^* q_o > 0$;
- (iv) Due to the linear homogeneity of the water quality technology Q , second stage purification is a break-even operation: $RCD\ I = \pi_{q\ell}^* \Delta q^* - \ell_q^* - \pi_{e\ell}^* e_q^* = 0$;
- (v) If $q^* > q_u$ the cost of assimilative services used by the industry is greater than the purification plant's labor cost, i.e. $RCD\ II = \pi_{e\ell}^* e_y^* - \ell_q^* > 0$.

The important allocative function of Lindahl prices can be understood even better by investigating how prices and quantities shift in response to exogenous shocks. Under a few qualifications (Pethig 1989b) changes in labor endowment (ℓ_o) and assimilative capacity (e_o) have the following effects: The welfare maximizing response to growth of factor endowments is an increase in both 'national product' and water quality. Labor growth raises both labor intensities and the real price for assimilative services, but this price and labor intensities decrease when nature's self-cleansing capacity improves. Responses of the real price of water quality to these changes depend on relative labor intensities in production.

2.3 Water Quality Management with Prices and Standards

Having set up the fictitious market economy as a benchmark, we now move closer to reality by adopting the following assumptions:

- (a) The water resource is publicly owned and managed by a government agency, called the water quality board.
- (b) There is **no market for water quality** ($p_q = dp_q = 0$); instead, water quality is now assumed to be politically determined (Baumol and Oates 1975) so that the previously endogenous variable q is substituted by the parameter q_s , denoted the **water quality standard**.
- (c) The water quality board takes care of **financing the plant's operation** by pursuing one of two strategies:

Strategy I. The board leaves the allocation of assimilative services to the competitive market,³ urging the purification plant to produce at **minimum cost**. It transfers the revenue $p_e e_o$ to the consumption sector, and then raises a lump-sum tax from consumers that covers the total cost $p_e e_q + p_\ell \ell_q$ of the purification plant. Consequently, the consumers' net tax is equal to $(-\pi_{el} e_o + \pi_{el} e_q + \ell_q = \ell_q - \pi_{el} e_y)$ so that the aggregate budget constraint of the consumption sector reads

$$(8) \quad \pi_{y\ell} y = \ell_o + \text{RCD II} \quad \text{with} \quad \text{RCD II} := \pi_{el} e_y - \ell_q$$

Strategy II. The water quality board imposes an industrial **sewage charge**, p_e , on all firms, but it exempts the purification plant from paying for its use of assimilative services. The sewage charge revenue is passed over to the purification plant under the provision that the plant adjusts its labor cost as to match exactly that sewage charge revenue. In other words, the board imposes the **cost-covering or self-financing constraint**

$$\text{RCD II} := \pi_{el} e_y - \ell_q = 0.$$

In what follows, these two strategies will be discussed successively.

³ This is a market for permits to use assimilative services. Total supply of assimilative services is e_o . The water quality board is a demander of these permits as are the polluting firms. But while the firms make use of their acquired permits to emit pollutants, the board uses its permits as input in its production of water quality.

Efficient Implementation of Water Quality Standards (Strategy I). Implementing Strategy I requires to substitute the endogenous variable q by the parameter q_s , the water quality standard. For convenience, we set $q_0 = dq_0 = 0$, so that $q_s = \Delta q_s$. It turns out that the decision problem for the industry is still the same as in the Lindahl procedure while the purification plant produces q_s at minimum cost without being concerned about how its activity will be financed.

Denote by q^* the water quality associated to a Lindahl equilibrium discussed in Section 2.2 and suppose that $q_s = q^*$ is incidently satisfied. Then the equilibrium allocation of Strategy I is obviously the Lindahl allocation so that the results from Section 2.2 carry over to this particular case. It is easy to generalize this argument to all equilibria under Strategy I. We conclude, therefore, that Strategy I is characterized by the properties:

- (i) Production is efficient, since (6) holds.
- (ii) Whenever $q_s < q_u$, one has $RCD II = \pi_{el} e_y - \ell_q > 0$.

The comparative statics of Strategy I are straightforward (Pethig 1989b), if one keeps in mind that the endogenous changes of water quality are now interpreted as parametric changes of the water quality standard. When the comparative statics of the Lindahl solution are compared to that of Strategy I (Pethig 1989b) it is easy to see that, with minor qualifications, all endogenous variables show the same directions of change as specified in the last paragraph of Section 2.2.

Cost-covering Purification and Water Quality Standards (Strategy II). In many countries this type of water quality management appears to be relevant: purification plants are often public enterprises that have to obey the constraint $RCD II = 0$. To characterize the equilibrium allocation associated to Strategy II consider the factor allocation $(e_q, \ell_q, e_y, \ell_y)$ where the water quality standard is given by $q_s = q_0 + Q(\ell_q, e_q)$. It can be shown (Pethig 1989b) that there is a function G , such that $(e_q, \ell_q, e_y = e_0 - e_q, \ell_y = \ell_0 - \ell_q)$ is an equilibrium factor allocation (satisfying $RCD II = 0$) if and only if $\ell_q = G(e_q)$. Moreover,

$$G_e \geq 0 \Leftrightarrow \sigma_y \leq 1,$$

where σ_y is the elasticity of substitution in the production of good Y. The function G offers a convenient way to address the efficiency issue with the help of Figure 1 which represents the economy's attainable allocations of productive factors, the factor box.

— Insert Figure 1 about here —

Assuming $\sigma_y = 1$ in Figure 1, the equilibrium function G translates into a horizontal line, say AB . Suppose, the water quality q_1 is to be implemented. The efficient production point would then be P_1 , but cost coverage requires to move to P'_1 where the q_1 isoquant intersects the line AB . The inefficiency implied by shifting from P_1 to P'_1 is easily measured by the amount $y_1 - y'_1$ of the consumption good wasted. As compared with P_1 , in P'_1 the sewage charge is too low: the shadow price of e_q at P'_1 (slope of the q_1 isoquant in P'_1) is greater than the actual sewage charge.

It is important to know, whether it is possible to implement a water quality standard, say $q_s = q_2$ in Figure 1 with the following properties: The labor intensity of purification is lower in case of self-financing (point P'_2) than in case of production efficiency (point P_2) — as drawn in Figure 1 — and that at the same time $q_2 < q_u$ holds — contradicting the constellation in Figure 1. It can be shown (Pethig 1989b) that *for all water quality standards in the relevant range, cost-covering purification implies inefficiently low industrial waste abatement resulting from an inefficiently low sewage charge.*

Figure 1 also allows to assess the impact of shifting the water quality standard from q_1 to q_2 ($q_2 > q_1$). The move from the old equilibrium P'_1 to the new one, P'_2 , is accompanied by an enormous decrease in labor intensity in the purification plant (which would have only slightly grown, if the move would have been from P_1 to P_2) and vice versa in the industrial sector. Now the shadow price of e_q is less than the industrial sewage charge implying a waste of consumption good equal to $y_2 - y'_2$. Observe finally, that the efficient implementation of the quality standard q_1 is linked to an excess of revenue over cost in the purification plant, whereas efficiency in implementing q_2 would require to run a deficit.

3. Sewage Charges versus Effluent Charges

We continue the analysis of the two-stage waste(water) treatment process in which intra-industrial waste abatement is followed by end-of-pipe purification. As in Strategy II of Section 2.3 the water quality board is assumed to levy a **sewage charge** on all firms that release their wastewater into the (public) sewerage. Recall that in Strategy II the purification plants released the purified (but not perfectly clean) water into the water resource free of charge. In contrast, we now introduce an additional emission charge, called **effluent charge** hereafter, on the purification plants which are based on the residual waste content of the purified water which is released into the recipient water

resource. Then the central question is what the efficiency implications of water quality management are when the sewage charge and the effluent charge are simultaneously levied in the two-stage purification process. We will scrutinize this issue within the following institutional arrangements: Purification plants may have to observe a cost-covering constraint, and/or it may be required by law that the revenues from effluent charges are earmarked in the sense that they have to be spent for subsidizing wastewater treatment processes.

Obviously, in order to analyze the allocative impact of an earmarked effluent charge we need to extend the model of Section 2 to a two-region economy. This is done in Section 3.1. Section 3.2 covers the policy strategies of earmarked and non-earmarked effluent charges when no cost-revenue constraint is imposed. The focus of Section 3.3 is on the impact of the two types of effluent charges in the presence of a cost-covering constraint.

3.1 The Two-region Economy

Recall that the water resource in the model of Section 2 was completely characterized by (e_o, q_o) . Correspondingly, in the two-region model each region has a water resource (e_{oi}, q_{oi}) , $i = 1, 2$. We set $q_{o1} = q_{o2} = 0$ for convenience, and assume that the regional water resources are completely independent from each other. For water resource i the predetermined water quality standard is q_{si} . The regional purification plants' production functions are

$$(9) \quad q_i = Q^i(e_{qi}, \ell_{qi}) \quad (i = 1, 2).$$

Each region produces the same consumption good Y via identical linear homogeneous production functions

$$(10) \quad y_i = Y(e_{yi}, \ell_{yi}) \quad (i = 1, 2).$$

The aggregate labor endowment is ℓ_o , and labor is perfectly mobile. Hence the relevant resource constraints are

$$(11) \quad \ell_o = \sum_i \ell_{qi} + \sum_i \ell_{yi} \quad \text{and} \quad e_{oi} = e_{qi} + e_{yi}.$$

The allocation of resources in this two-region economy is efficient relative to the given water quality standards q_{s1} and q_{s2} , if total income $y_1 + y_2$ is maximized subject to

(10) – (12) and subject to $q_i = q_{si}$ ($i = 1, 2$). Not surprisingly, the efficiency conditions (for an interior solution) turn out to be given by (6) with subscripts $i = 1, 2$ attached.

Suppose now there are markets for labor and for good Y both of which are nation-wide and perfectly competitive. Then the law of indifference requires the prices for labor and industrial output not to differ interregionally. With identical linear homogeneous production technology for good Y the industrial output cannot be positive in both regions unless the sewage charge is the same across regions. Consequently, it seems appropriate to assume sewage charges to be uniform across regions.

In order to specify the equilibrium concept for the economy, the sewage charge and the effluent charge have to be made precise in formal terms. As before the rate of the sewage charge is denoted p_e so that $p_e e_{yi}$ is the revenue from the sewage charge in region i . The rate of region i 's effluent charge is denoted p_{ti} . It is levied on the residual industrial waste that is finally discharged into the region's water resource after treatment in the purification plant. Its revenue can be easily calculated since, by assumption, the purification plant sees to it that the water quality q_i exactly meets the predetermined standard q_{si} . Defining $e_{qi}^s = \tilde{A}^i(q_{si})$ by $q_{si} = Q^i(0, e_{qi}^s)$ it is straightforward that

$$(12) \quad e_{ni} := e_{oi} - e_{qi}^s = e_{oi} - \tilde{A}^i(q_{si}) =: F^i(q_{si}, e_{oi})$$

$\quad \quad \quad - \quad \quad +$

is the net amount of waste for which the effluent charge is due, if e_{oi} is the maximum assimilative capacity of the regional water resource and if the quality standard q_{si} is to be implemented. Using this information the following equilibrium concept is straightforward:

An **equilibrium of the two-region economy** is constituted by an **allocation** $[(e_{qi}, e_{yi}, \ell_{qi}, \ell_{yi}, y_i; q_{si})_{i=1,2}]$, by a **price vector** $(p_e, p_\ell := 1, p_y)$, and by a **tax-subsidy vector** $[(b_i, z_i)_{i=1,2}]$ such that the following conditions hold:

- (i) The aggregate resource constraints (11) are satisfied;
- (ii) Regional industries maximize profits, i.e. (e_{yi}, ℓ_{yi}, y_i) maximizes g_i subject to (10) with $g_i := p_y y_i - \ell_{yi} - p_e e_{yi}$.
- (iii) The consumption sector's budget constraint holds, i.e. $\ell_0 + \sum_i g_i + \sum_i s_i + \sum_i (b_i - z_i) = \sum_i p_y y_i$, where $s_i := p_e e_{yi} - \ell_{qi} - b_i + z_i$ denotes the surplus of regional

purification plants⁴ to be transferred to the consumption sector.

- (iv) The purification plants implement the **water quality standards** q_{si} ($i = 1, 2$) following, **alternatively**, one of two strategies:

Cost covering: The purification plant's action is such that

$$(13) \quad (e_{qi}, \ell_{qi}) \text{ satisfies } s_i := p_e e_{yi} - \ell_{qi} - b_i + z_i = 0.$$

Cost minimization (with s_i unconstrained): The purification plant's action is such that

$$(14) \quad (e_{qi}, \ell_{qi}) = \arg \min (\ell_{qi} + p_e e_{qi}) \text{ subject to (9) for } q_i = q_{si};$$

- (v) The tax-subsidy vector $[(b_i, z_i)_{i=1,2}]$ is specified, **alternatively**, by one of the following financial arrangements:

Lump-sum transfer policy: The revenues from the effluent charge are transferred lump-sum to the consumption sector, i.e.

$$(15) \quad z_i = 0 \text{ and } b_i = p_{ti} F^i(q_{si}, e_{oi}), \text{ with } F^i \text{ as defined in (12).}$$

Earmarking policy: The revenues from the effluent charge of region i are earmarked for subsidizing wastewater treatment in region j ($i, j = 1, 2; i \neq j$), i.e.

$$(16) \quad b_i = p_{ti} F^i(q_{si}, e_{oi}) = z_j \text{ and } b_j = z_i = 0.$$

3.2 Cost Minimizing Purification without Revenue-Cost Constraints

To simplify the analysis assume, in what follows, that the production functions (10) are Cobb-Douglas, i.e.

$$(10') \quad y_i = \ell_{yi}^\alpha \cdot e_{yi}^{1-\alpha} \quad \text{with } \alpha \in (0, 1).$$

In that case, industrial profit maximization implies

⁴ Observe that for $b_i = z_i = 0$ the surplus s_i is equal to RCD II as defined in (8).

$$(17) \quad p_e = \frac{1-\alpha}{\alpha} \cdot \frac{\ell_{yi}}{e_{yi}}$$

When combined with the necessary equilibrium condition

$$(18) \quad p_y y_i = \ell_{yi} + p_e e_{yi},$$

it is easy to see that for given q_{si} the purification plant's activity (ℓ_{qi}, e_{qi}) is uniquely determined by p_e . In particular, the cost minimizing allocation $(\ell_{qi}, e_{qi})_{i=1,2}$ is independent of how the tax-subsidy scheme $[(b_i, z_i)_{i=1,2}]$ is specified.

It is shown in Pethig & Fiedler (1989) that there is a unique equilibrium of the two-region economy with cost-minimizing purification plants in which the interregional distribution of labor is endogenously determined. In that equilibrium, as in the one-region model of the previous section, both purification plants have to generate a surplus $p_e^* e_{yi}^* > \ell_{qi}^*$ independent of how the tax-subsidy scheme is specified. In other words: *Whenever the cost minimizing strategy (14) is applied, the resource allocation turns out to be efficient. Whether earmarked or not, effluent charges have no allocative impact at all, i.e. they don't disturb efficiency: Once the price signals of sewage charges are used in an appropriate way, effluent charges have no additional or even independent role to play in cost minimizing water quality management.*

At the first glance this conclusion is intriguing if not disturbing because it seems to be straightforward that for efficiency reasons the emission of pollutants into the water resource should be priced, e.g. by an effluent charge. In order to understand why effluent charges are irrelevant and ineffective in the present specification of our model, recall that the regional purification plants meet their respective quality standards *by assumption*. Since the standards q_{si} translate uniquely into net emission flows e_{ni} according to (12), purification plants do not respond at all to the levying or to the change in the rate of an effluent charge. But what is the reason for achieving allocative efficiency nonetheless? It is the cost minimization strategy (14) which gives the correct price signal. Essentially this procedure implies that the purification plants pay the price p_e (called the sewage charge – somewhat incorrectly) for its use e_{qi} of assimilative services. What is really needed for efficiency is not a two-stage charge (i.e. the sewage charge and the effluent charge) in the two-stage purification process, but a uniform price, p_e , for all users of assimilative services: The industry pays that price for its

demand e_{yi} to assimilate pollutants and the purification plant pays the same price for its use of assimilative services to "produce" water quality.⁵

3.3 Zero Surplus and Non-Earmarked Effluent Charges in a One-Region Economy

Before continuing the interregional analysis it is important to understand what the joint impact of a sewage charge and an effluent charge is in an *isolated region* when a *cost-covering constraint* is imposed. Observe that this is an immediate extension of the analysis of Section 2.3.

With s_i as defined in (13), the zero-surplus constraint $s_i = 0$ can be written as

$$(19) \quad \ell_{qi} = p_e e_{yi} - \delta_i \quad \text{with} \quad \delta_i := b_i - z_i = \text{RCD}_i \text{ II.}$$

When combined with (17) and (10'), equation (19) yields

$$(20) \quad \ell_{qi} = (1-\alpha)a_{oi} - \alpha\delta_i \quad \text{and} \quad \ell_{yi} = \alpha\ell_{oi} + \alpha\delta_i, \quad \text{where} \quad \ell_{oi} := \ell_{qi} + \ell_{yi}.$$

If the economy consists of region i only, (setting $a_{oj} = e_{oj} \equiv 0$ for $j \neq i$) and the effluent charge strategy (15) is implemented (with $z_j = b_j \equiv 0$; $j \neq i$), the complete equilibrium solution can be calculated from (9), (10'), (11), (15), (17), (18), and (20).

It is shown in Pethig & Fiedler (1989) that there is a function R such that

$$(21) \quad r_i := (Q_e^i/Q_\ell^i - Y_{ei}/Y_{\ell i}) = R^i(p_{ti}) \quad \text{and} \quad R_p^i < 0.$$

Moreover, we established in the Section 2.3 that $R^i(p_{ti}) > 0$ for $p_{ti} = 0$. It can also be shown that total production of the consumption good Y is a strictly concave function,

say \mathcal{Y}^i , of the effluent charge p_{ti} satisfying $\left. \frac{d\mathcal{Y}^i(p_{ti})}{dp_{ti}} \right|_{p_{ti}=0} > 0$. In other words the introduction of an effluent charge increases the efficiency in the one-region economy.

The strict concavity of function \mathcal{Y}^i implies that there is a unique rate p_{ti}^* of the effluent

⁵ This view may be rejected on the grounds that charging the purification plant for "producing" water quality amounts to accepting the 'pollutees-pay-principle'. But note that the market economy is not characterized by the polluters-pay- or the pollutees-pay-principle but by the 'users-pay-principle'. See also Pethig (1989a).

charge for which the associated equilibrium allocation is efficient. p_{ti}^* also satisfies $R^i(p_{ti}^*) = 0$ so that there is a unique positive value of p_{ti} , say p_{ti}^* , satisfying $R^i(p_{ti}^*) = 0$. In other words,

$$\frac{dY^i(p_{ti})}{dp_{ti}} \geq 0 \Leftrightarrow R^i(p_{ti}) \leq 0.$$

It follows that the constellation $r_i > 0$ covers the relevant range. Under this assumption Pethig & Fiedler (1989) calculated the comparative statics for the one-region economy. Here we content ourselves with offering a few comments on the impact of effluent charge changes on the output of good Y: Changes in the rate of the effluent charge turn out to have an unambiguous positive effect both on the sewage charge, p_e , and on the price p_y . The rise of p_e means that the purification plants shift (part of) the burden of the effluent charge onto the indirect dischargers. The industrial sector, in turn, shifts that burden further to the consumers by raising the price for good Y. Furthermore, an increase in the effluent charge rate causes a labor shift away from the purification plant to the industrial sector. This displacement effect decreases the labor intensity in the purification plant and increases the industrial labor intensity. An increase in the rate of the effluent charge also raises the (inefficiently low) industrial abatement activities and reduces the (inefficiently high) operating level of the purification plants.

3.4 The Zero-Surplus Constraint in the Two-Region Economy

Returning now to the case of two regions observe that an equilibrium of the two-region economy is determined by the equations (10'), (9) with $q_i = q_{si}$, (17), (18), and (20). This system of equations exhibits a special interdependence between the sewage charge p_e and the interregional labor allocation (ℓ_{o1}, ℓ_{o2}) which allows to establish that this allocation (ℓ_{o1}, ℓ_{o2}) satisfies $\ell_o = \ell_{o1} + \ell_{o2}$ for a particular value of the sewage charge $p_e = p_{e1} = p_{e2}$ only. Hence the two-region economy exhibits a unique equilibrium for every given tax-subsidy scheme (δ_1, δ_2) . Closer inspection shows that the interregional labor allocation (ℓ_{o1}, ℓ_{o2}) clearly depends on the tax-subsidy scheme in operation which makes the analysis fairly complex. Therefore, we choose to ignore exogenous changes in q_{si} and e_{oi} in the following and concentrate, instead, on how changes of the effluent charge affect the aggregate 'national product' $y := y_1 + y_2$. Tedious calculations (Pethig & Fiedler 1989) yield

$$(22) \quad \hat{y} = \frac{Y_\ell}{y \, r_{q1} r_{q2}} \sum_{i \neq j} \left[\alpha \delta_i r_{qj} r_i + \frac{(1-\alpha) \beta_i \rho_j r_y (r_i - r_j)}{\rho_1 r_2 + \rho_2 r_1} \right] \hat{\delta}_i,$$

where "hats" indicate relative changes of the respective variable and where $r_{qi} := Q_e^i / Q_\ell^i$, $r_{yi} = Y_{ei} / Y_{\ell i}$, $r_y = r_{yi} = r_{yj}$, $r_i := r_{qi} - r_y$ and $\rho_i = \ell_{yi} r_{qi}$. In (22), the first term in the sum represents the relative change of y following a change in δ_i . The second term gives us the impact on y of an interregional labor shift. Suppose, $\hat{\ell}_{o2} > 0$ (presupposing $\hat{\delta}_1 > 0$ and/or $\hat{\delta}_2 < 0$). In that case the sign of the pertaining change in y is determined by the sign of $r_1 - r_2$. The term r_i can be viewed as a measure of regional (in)efficiency that indicates efficiency for $r_i = 0$ and growing inefficiency with increasing r_i in absolute terms. Consequently, $r_1 > r_2$ means that the allocation in region 1 is less efficient than in region 2. Hence an increase of δ_1 causes, ceteris paribus, a labor shift to region j via (31), and this displacement effect increases [decreases] the overall production of good Y if and only if region j is more [less] efficient than region i .

With (22) we are in the position to consider the allocative impact of raising effluent charges separately for the tax-subsidy strategies (15) and (16). Starting with the strategy (15) of implementing a **non-earmarked effluent charge**, we specify $\delta_i = b_i$ (or $\delta_i = p_{ti}$, for simplicity) and $\hat{\delta}_i = \hat{p}_{ti}$ for $i = 1, 2$. Similar as in the one-region case of Section 3.3, the total consumption good produced depends on the regional effluent charges: $y = \mathcal{Y}(p_{t1}, p_{t2})$. One can show that there is a pair of positive effluent charges (p_{t1}^*, p_{t2}^*) such that $\mathcal{Y}(p_{t1}^*, p_{t2}^*)$ is a global maximum on \mathbb{R}_+^2 . Unfortunately, however, y is not monotonically increasing in p_{t1} and p_{t2} . But starting with $p_{t1} = p_{t2} = 0$, there exists a strategy of continuously non-decreasing changes of p_{t1} and p_{t2} such that $\mathcal{Y}(p_{t1}, p_{t2})$ strictly rises until $\mathcal{Y}(p_{t1}^*, p_{t2}^*)$ is reached (Pethig & Fiedler 1989).

Turning now to the case of **earmarked effluent charges**, recall that under the tax-subsidy strategy (16) we specify $\delta_i = -\delta_j = b_i$ and $\delta_k = \hat{p}_{ti}$ for $k = 1, 2$. To fix our ideas, let $i = 1$. Then (22) can be rearranged to read

$$(22') \quad \hat{y} = \frac{Y_\ell}{y \, r_{q1} r_{q2}} \left[\alpha b_1 r_y + \frac{(1-\alpha) b_1 r_y \sum_{i \neq j} \beta_i \rho_j}{\rho_1 r_2 + \rho_2 r_1} \right] (r_1 - r_2) \hat{p}_{t1}.$$

Moreover, considering the negative sign of δ_2 , one can show that $d(r_1 - r_2)/dp_{t1} < 0$. Two cases have to be distinguished: (i) If $r_1 > r_2$ for $p_{t1} = 0$, then raising p_{t1} implies efficiency gains ($\hat{y} > 0$) up to some effluent charge p_{t1}' for which $r_{q1} = r_{q2}$. Any further

increase of p_{t1} beyond p'_{t1} would diminish the overall production of good Y ($\hat{y} < 0$). (ii) If $r_1 < r_2$, then $\mathcal{Y}(p_{t1}) < \mathcal{Y}(0)$ for all positive p_{t1} .

The intuition behind these results is straightforward: *If the effluent charge is levied on that region which was more [less] inefficient than the other one in the initial situation, then the taxed region's efficiency gain will [not] overcompensate the subsidized region's efficiency loss for low rates of the effluent charge. In both cases it is true that the overall production of good Y sinks below its initial level for sufficiently large effluent charge rates.*

The policy implications of these results are also clear-cut: If politicians cannot be convinced of going for the first-best strategy of abstaining from both cost-revenue constraints and from earmarking then they should be at least induced not to earmark the proceeds of effluent charges for municipal wastewater treatment.

4. Pricing the Quality and the Quantity of (Raw) Water

As described in the introduction of this paper we now turn to the interface of water quality and water quantity management. The subsequent analysis is simplified by omitting the purification plants – and hence the two-stage purification process altogether. On the other hand, production activities for drinking water and for raw water quality are now added to the analysis. Land is introduced as a production factor in addition to labor. Land is productive for the industry (and/or agriculture) and can be alternatively used for water protection areas. To keep the analysis simple, water pollution outside of water protection areas is considered so severe that raw water used for the generation of drinking water must exclusively be taken from these areas. Their size defines an upper bound for the amount of drinking water that can be generated, but it also influences the quality of raw water; the larger the body of water in that area, the higher its quality resulting from given pollution spillovers.

In the following, a general equilibrium model is constructed with drinking water produced from raw water with the help of labor whose productivity increases with raw water quality. Raw water quality is assumed to depend on both the size of the water protection area and on that amount of assimilative services of the raw water resource which is not used for waste assimilation.

After the description of the model we investigate the characteristics of efficient shadow

prices. Assimilative services of the raw water resource and (hence) raw water quality turn out to be always scarce. Therefore, the price of drinking water must be higher than average operating costs of the water work owing to a mark-up for raw water quality. Another mark-up is due if raw water carries a positive rent. It is shown that efficiency may, but need not necessarily imply raw water scarcity. The remaining part of the paper concentrates on specifying conditions for raw water scarcity.

4.1 The Model

For the production of drinking water the intermediate good **raw water** is needed in sufficient quantity and appropriate purity (**raw water quality**). A **raw water enterprise** is supposed to provide three outputs: the quantity of raw water, the quality of raw water, and assimilative services. Denote by b_q the amount of land (**water protection area**) owned by this firm for the purpose of protecting from pollution the water resource located on or underneath this land (**raw water resource**). By assumption, water from outside the protected area is too polluted to be used for the generation of drinking water. The availability of raw water is therefore constrained by the size of the raw water resource. Suppose, for simplicity, that the maximum supply (per period) of raw water, r , is proportional to the size of the water protection area:⁶

$$(23) \quad r = \rho b_q \quad \text{with } \rho > 0.$$

Being the owner of land b_q the raw water enterprise prohibits, of course, the direct discharge of pollutants into the raw water resource, but it cannot prevent the amount

$$(24) \quad e_y = \mu m_y, \quad \text{with } \mu \in [0,1),$$

of pollutants from spilling over – or leaking – into the restricted zone. In (24) m_y denotes the flow of pollutants emitted by the production sector.

⁶ r is that amount of raw water which can be withdrawn without any reduction of the water table. It is implicitly assumed in this paper that the upper bound r for water withdrawal is always observed (due to effective enforcement) – in contrast to empirical evidence in some regions. The impact of relaxing this assumption is studied in Pethig (1988) and Linde (1988). In a spatial economy – as in the real world – one encounters the additional possibility of local drinking water excess demands implying local raw water scarcity (Brösse 1980). In Germany this mismatching of demand and supply is balanced by large-scale compound systems for interregional raw water transfers. In the present paper this issue is ignored.

As before, the industry produces a consumption good Y by means of labor ℓ_y and generates the flow of emissions, denoted m_y . In addition, land b_y is used as a productive factor. Hence good Y is produced by means of the concave and linear homogeneous production function \tilde{Y} , where

$$(25) \quad y = \tilde{Y}(\underset{+}{\ell_y}, \underset{+}{b_y}, \underset{+}{m_y}),$$

and where the domain of function \tilde{Y} is similarly constrained as that of function Y from equation (1). To simplify the analysis the production function \tilde{Y} from (23) is assumed to be weakly separable (Berndt and Christiansen 1973, p. 404) in the sense that

$$(25') \quad y = \tilde{Y}(a_y, b_y, e_y/\mu) = Y[a_y, H(b_h, e_h)],$$

where $b_h = b_y$, $e_h = e_y$, and where H is linear homogeneous.

For any given b_q and q the assimilative capacity of the raw water resource is $A(b_q, q)$. That is, if the amount $A(b_q, q)$ of pollutants spills over into the raw water resource period by period, then the raw water quality does not change in time. Function A is increasing in b_q and decreasing in q on some non-empty interval $(q_0, q_m]$. More specifically, suppose A has a unique maximum with $q_0 = \arg \max E(b_q, q)$ for all b_q and let

$$e := \max_q A(b_q, q) = \eta b_q \quad \text{with } \eta > 0.$$

Clearly, $e = \eta b_q$ can be interpreted as the maximum **supply of assimilative services** or as the assimilative potential of the raw water resource. Correspondingly, the maximal emission flow sustainable in the long run is ηb_q . In what follows we disregard all (inefficient) raw water qualities $q < q_0$.

As argued in the previous sections the assimilative capacity can be either used for waste assimilation (e_y) or for natural improvements of raw water quality (e_q), where e_q is defined as that amount of assimilative services which is not used for waste assimilation:

$$(26) \quad e_q + e_y = \eta b_q.$$

Restricting the analysis to stationary ecological states we require the equation $e_y = A(b_q, q)$ always to be satisfied. In view of (26) we therefore obtain

$$(27) \quad \eta b_q - e_q - E(b_q, q) = 0.$$

Equation (27) is an implicit ecological production function for raw water quality, sustainable in the long run by means of the productive factors e_q and b_q . For q in the interval $[q_0, q_m]$ the implicit function (27) can be rewritten in explicit form as

$$(28) \quad q = Q(b_q, e_q),$$

where the properties of Q are determined by the properties of A . Since the "ecological" information about function E appears to be still unsatisfactory we proceed by considering two *alternative* specifications of function E :

Assumption A: Q satisfies $Q_b, Q_e > 0$, and Q is concave and linear homogeneous⁷.

Assumption B: The function A takes the special form

$$(29) \quad A(b_q, q) = b_q \cdot F(q).$$

Function F from (29) satisfies $F(q_0) = F(q_m) = 0$ and is strictly concave on $[q_0, q_m]$. As a consequence of (29) the ecological relationship (27) can be transformed into a production function $Q: D_q \rightarrow [q_0, q_m]$ such that

$$(28') \quad Q(b_q, e_q) = F^{-1}\left(\eta - \frac{e_q}{b_q}\right)$$

and $D_q := \{(b_q, e_q) \mid b_q F(q_0) \geq \eta b_q \geq e_q \geq 0, e_q \geq 0, b_q > 0\}$. The function Q from (28') is increasing in e_q , decreasing in b_q and non-concave.

Drinking water is produced by the **water work** with the help of the production function

$$(30) \quad w = \min \left[r_w, W(\ell_w, q_w) \right],$$

+ + +

⁷ It is shown by Pethig & Fiedler (1992) that the assumptions introduced for the assimilation function A together with equation (27) are compatible with a function Q on $[q_0, q_m]$ which is concave and has positive derivatives. Observe also that Q is flat at the level $q = q_m$ for sufficiently large input combinations.

where ℓ_w represents the labor input, r_w the quantity and q_w the quality of raw water. The minimum condition in (30) reflects the obvious limitation of drinking water production by the availability of raw water input. If raw water is abundant, the (unconstrained) function W is the production function of drinking water. W is assumed to be increasing in both arguments, concave and linear homogeneous. The description of the supply side is completed by listing all resource constraints:

$$(31) \quad \begin{array}{ll} q_w \leq q & \ell_y + \ell_w \leq \ell_o \\ w_d \leq w & b_y + b_q \leq b_o \\ y_d \leq y & e_y + e_q \leq \eta b_q \\ & r_w \leq r \end{array}$$

The inequalities (31) conveniently summarize the commodity space of the economy. There are two conventional productive factors: labor and land; two end products: drinking water and good Y ; in addition, there are three natural resources or "environmental goods": (the quantity of) raw water, raw water quality, and assimilative services of the raw water resource. The two primary factors, land and labor, ultimately produce two end products, namely drinking water and good Y . In the model's "ecological core", three intermediate outputs, namely raw water, assimilative services and raw water quality, are produced with the help of the inputs land (water protection area) and assimilative services.

It remains to specify the demand side of the model. As in the previous sections our focus is on allocative efficiency rather than on distributional issues. Therefore we proceed as before by assuming that all n consumers have identical, strictly quasi-concave and homothetic preferences represented by

$$(29) \quad u = U(y_d, w_d).$$

$\begin{array}{cc} + & + \end{array}$

4.2 Efficient Shadow Prices

To characterize an efficient allocation, consider the problem of maximizing the representative consumer's utility (29) subject to (23), (24), (25'), (28), (30), and (31). The associated Lagrangean is

$$\begin{aligned}
L = & U(y_d, w_d) + \lambda_y[Y(h_y, \ell_y) - y] + \lambda_w[W(\ell_w, q_w) - w] + \lambda_h[H(b_h, e_h) - h] \\
& + \lambda_q[Q(b_q, e_q) - q] + \lambda_r(r_w - w) + \lambda_\rho(\rho b_q - r) + p_y(y - y_d) + p_w(w - w_d) + \\
& + p_q(q - q_w) + p_h(h - h_y) + p_b(b_o - b_h - b_q) + p_e(\eta b_q - e_h - e_q) + \\
& + p_a(\ell_o - \ell_y - \ell_w) + p_r(r - r_w).
\end{aligned}$$

In the case of assumption A, the Kuhn–Tucker conditions are necessary and sufficient for an efficient allocation. Under assumption B they are only necessary. When the attention is restricted to interior solutions, it is easy to show that the shadow prices p_v for $v = a, b, e, h, q, w, y$ are positive. But raw water may be either scarce ($p_r > 0$) or a free good ($p_r = 0$). More specifically, $p_r > 0$ implies $r = r_w = w = W(\ell_w, q_w)$ and $p_r = 0$ implies $r \geq r_w \geq w = W(\ell_w, q_w)$. To see why raw water may or may not be scarce, observe that $r_w > 0$ implies $p_r = \lambda_r$, and that $w \geq w_d > 0$ implies $p_w = \lambda_w + p_r = U_w > 0$. Moreover, $p_a > 0$ and $W_\ell > 0$ implies $\lambda_w > 0$, which can be shown to assure $w = W(\ell_w, q_w)$ and $r_w \geq W(\ell_w, q_w)$. But $\lambda_w > 0$ is still compatible with $r > r_w$. Only if $\lambda_r = p_r > 0$ then $w = r_w = W(\ell_w, q_w)$. To sum up, in an interior solution the efficient price of drinking water is

$$p_w = \lambda_w + p_r \geq \lambda_w > 0,$$

where $p_r \geq 0$ is the scarcity price of raw water and where λ_w is the marginal-cost price of generating drinking water from raw water in the water work. In other words, λ_w is the efficient price of drinking water provided that raw water is abundant. To illustrate this relationship recall that $r_w = W(\ell_w, q_w)$ for $p_r > 0$ and $r_w \geq W(\ell_w, q_w)$ for $p_r = 0$. Therefore, it is possible to write the water work's profit as

$$(30) \quad p_w \{\min[r_w, W(\ell_w, q_w)]\} - p_a \ell_w - p_q q_w - p_r r_w = p_w^n \cdot W(\ell_w, q_w) - p_\ell \ell_w - p_q q_w$$

with $p_w^n := \lambda_w = p_w - p_r > 0$ being the **producer price of drinking water**. Since the Kuhn–Tucker conditions imply marginal-cost pricing in the water work, linear homogeneity of W requires $p_w = p_\ell(\ell_w/w) + p_q(q_w/w) + p_r$. Hence, the efficient **consumer price of drinking water** must exceed the operating cost of the water work per unit of drinking water, i.e. $p_\ell(\ell_w/w)$, by a mark-up for raw water quality, $p_q(q_w/w)$, and by the raw water rent p_r per unit of water. To see how the mark-up for raw water quality is determined, consider the profit of the raw water enterprise:

$$\begin{aligned}
 (31) \quad G^q(b_q, e_q) &:= p_q Q(b_q, e_q) + p_e \eta b_q + p_r \rho b_q - p_b b_q - p_e e_q = \\
 &= p_q \cdot Q(b_q, e_q) - p_b^n \cdot b_q - p_e \cdot e_q
 \end{aligned}$$

with $p_b^n := p_b - \eta p_e - \rho p_r$ being the raw water producer's effective (or net) price for the water protection area. It is smaller than the price for land because of the revenue generated by the two joint products of the water protection area: assimilative services and raw water. The Kuhn–Tucker conditions imply that for b_q (and therefore r and w) to be positive in an efficient allocation p_b^n must be *positive* under assumption A, but *negative* under assumption B. It is interesting to note that in the second way of writing the profit in (31) it appears as if the raw water enterprise is simply a producer of raw water quality. But this enterprise does indeed produce the two outputs, raw water and assimilative services, in addition to raw water quality.

Given assumption A and the linear homogeneity of Q , the price of raw water quality is specified by $p_q = p_b^n(b_q/q) + p_e(e_q/q)$. It consists of the sum of the net price for the water protection area and the price for assimilative services used by the raw water enterprise. If assumption B holds, the Kuhn Tucker conditions also require marginal-cost pricing by the raw water producer, but $Q_b/Q_e = p_b^n/p_e$ is equal to $p_b^n b_q + p_e e_q = 0$ so that $G^q(b_q, e_q) := p_q Q(b_q, e_q) > 0$ owing to (31). In this case, the price for raw water quality cannot be readily split up in its factor cost components.

The information that p_r can, but need not be positive is not entirely satisfactory, because we do not know whether there is any specification of the model exhibiting an efficient allocation in which the price of raw water is positive. Additional insight is readily obtained, however, for the limiting case in which no pollution spillover occurs at all into the water protection area ($\mu = 0$): It is shown in Pethig & Fiedler (1992) that *under this assumption, raw water always turns out to be scarce*.

In view of the structure of our model, this result clearly confirms one's intuition. Recall that the raw water supply is proportional to the size of the water protection area, whose extension is costly because land has positive opportunity costs. Therefore, the scarce resource land would be wasted if raw water were in excess supply. The scarcity of land makes high quality raw water scarce with its price matching the marginal opportunity costs of the water protection area.

Though it is important to know how the price of raw water is affected when μ tends to zero, $\mu > 0$ is, of course, the *raison d'être* of the problem under consideration. Is there a reason to believe that the scarcity result for $\mu = 0$ could be reversed in case of $\mu > 0$? To see the logic of this possibility suppose for simplicity the flow of pollutants, e_h , is constant. Then raw water quality varies inversely with the size of the water protection area. Suppose, moreover, that it is technically infeasible (prohibitively costly) to generate drinking water from raw water whose quality is below some given threshold value. In this somewhat pathological scenario the threshold value for raw water quality determines a minimum size of the water protection area which may induce a raw water supply in excess of drinking water demand. In Section 4.3 we provide more information about this issue by taking account of the two alternative assumptions A and B on the production of raw water.

4.3 The Scarcity of Raw Water

Linear homogeneous production of raw water quality. Assume first function Q satisfies assumption A. Moreover, let the property rights for all environmental goods be exclusively assigned to and costlessly enforced by the raw water enterprise so that there is a competitive market for each of the seven commodities with prices p_a , p_b , p_e , p_q , p_r , p_w , and p_y . Since the model is well behaved in the Arrow–Debreu sense, a general competitive equilibrium exists and is Pareto efficient. In the following our attention is focused on the question of whether raw water is a scarce natural resource when pollution spills over into the water protection area.

To answer this question consider an initial state of competitive equilibrium of the economy in which raw water is abundant and investigate how the excess supply of raw water responds to shifts in the endowment of land and labor and to shifts of consumers' preferences. Successive increases in the endowment of labor can be interpreted as mimicking economic growth with its increasing pressure on the use of natural resources. Shifts in consumer preferences are appropriate to model differences in demand side pressure on water resources interpreted either as a particular country's changing preferences or as cross-country comparison. A very simple and convenient way to formalize such a demand shift is to specify the utility function (29) by

$$(29') \quad u = \min [w, \gamma \cdot y] \text{ with } \gamma > 0.$$

Moreover, to obtain informative results we further specify the production functions W , Y , H , and Q to be Cobb–Douglas, and we set $(\ell_w W / w) = (\ell_y Y / y)$. Under these

restrictions it can be shown (Pethig & Fiedler 1992) that if the initial general competitive equilibrium is characterized by excess supply of raw water at price zero, then raw water becomes less abundant — and, in the long run, possibly scarce — with increasing labor endowment ℓ_0 and with decreasing land endowment b_0 .

The effect on raw water excess supply of an increase in the demand parameter γ is not clear-cut. It is safe to argue, however, that with increasing γ the excess supply of raw water tends to diminish. Observe that ρb_0 is the maximum possible supply of raw water and that $W(\ell_0, q_m)$ is the maximum possible supply of drinking water under the proviso that there is no shortage of raw water. Obviously, $W(\ell_0, q_m) > \rho b_0$ is a sufficient condition for a tendency of raw water excess supply to diminish with successive increases of γ . In fact, under the condition $W(\ell_0, q_m) > \rho b_0$ there is always a $\bar{\gamma} > 0$ such that raw water is scarce for any $\gamma > \bar{\gamma}$.

Similar considerations hold with respect to changes in labor and land endowments. It can be shown that for any b_0 and γ there is a positive number c such that raw water carries a positive economic rent, if and only if $\ell_0 > c$.

The rationale of the above arguments for raw water scarcity is straightforward. Owing to the joint production property of the three goods raw water quality, assimilative services and raw water supply, the supply of raw water is not responsive to changes of the labor endowment as long as $p_r = 0$. In other words, if the labor endowment is sufficiently low then raw water is in excess supply. But economic growth (increasing ℓ_0) eventually turns raw water into a scarce resource.

To understand why the rent of raw water may be positive or zero in equilibrium, recall that the raw water producer's decision to raise its demand for land simultaneously increases both the maximum supply of raw water and the supply of assimilative services of the raw water resource. If for given amounts of pollutants a large water protection area is needed to achieve a raw water quality appropriate for generating drinking water, then the amount of raw water available in the large water protection area might be in excess supply, i.e. a free good. Conversely, if raw water pollution is not a severe problem then raw water carries a scarcity price.

Zero homogeneous production of raw water quality. Suppose now assumption B governs the "production" of raw water quality. Then function Q turns out to be non-concave. An immediate implication is that conventional methods may fail to characterize Pareto-efficient allocations. Moreover, price-taking profit maximization may, but need

not, be defined. In fact, it is true that under assumption B the profit function $G^q(b_q, e_q)$ from (31) does not exhibit a maximum on its domain D_q for any given set of prices $(p_b, p_e, p_r) \in \mathbb{R}_+^3$. Hence under assumption B the economy cannot attain a competitive equilibrium with a complete set of markets. In other words, it is not possible to decentralize Pareto efficient allocations by competitive prices.

Alternative routes to proceed are to consider the raw water enterprise as a (regulated) private monopoly or as a public enterprise. Depending on the regulations imposed it is likely that the associated equilibrium yields a second best allocation in which prices are known to be unreliable indicators of scarcity. However, Pethig & Fiedler (1992) were able to show that the raw water enterprise can achieve production efficiency by the strategy of cost covering

$$(32) \quad G^q(b_q, e_q) = -p_b^n b_q - p_e e_q = 0$$

combined with a choice of its input levels guided by

$$(33) \quad \frac{W_q}{W_\ell} \frac{Q_e}{H_e} = \frac{Y_h}{Y_\ell} = \frac{p_h}{p_\ell}$$

To obtain specific results we simplify the production functions H, Q, W, and Y again, similar as in the preceding subsection. The functions Y, W, and H are assumed Cobb–Douglas and function Q is determined as $Q(b_q, e_q) = (e_q/b_q)^\delta$. The demand side is given by (29'). Under these restrictions it follows that if the economy has an initial competitive equilibrium characterized by excess supply of raw water at price zero, then *raw water becomes less abundant – and, in the long run, possibly scarce – with increasing demand parameter γ , with increasing labor endowment ℓ_0 , and with decreasing land endowment b_0 .*

The model also implies that the real price of drinking water and raw water quality increases with diminishing raw water abundance. Moreover, it can be demonstrated along the same lines as in the preceding section that raw water becomes scarce in a growing economy (increasing ℓ_0). Indeed if assumption B holds and the (public) raw water enterprise observes the equations (32) and (33) one can even spell out necessary and sufficient conditions for *the price of raw water being positive ($p_r > 0$) in competitive equilibrium* (Pethig & Fiedler 1992). Hence the markedly different technological hypotheses A and B yield similar results on raw water abundance.

It is interesting to assess the merits of the so called "Wasserpennig" (water penny) as introduced in several German states in the light of the preceding analysis. The "water penny" is a charge on the withdrawal of raw water, whose allocative impact depends crucially on how drinking water was priced prior to its introduction. Suppose that drinking water prices were designed to cover the (average) operating costs of the water works before the implementation of the water penny. Then the water penny enhances allocative efficiency as long as its rate is not too high. This conclusion must be considered with the proviso, however, that real-world water management (in the absence of water charges) is likely to involve additional distortions other than the neglect of the scarcity of raw water quality and raw water. In such second-best scenarios the impact on welfare of economic policy interventions like the water penny is difficult to determine.

5. Concluding Remarks

The preceding analysis of water quality management (Sections 2 and 3) yielded a number of unexpected results. If assimilative services of the water resource are priced by levying a sewage charge (Section 2) cost-covering purification is shown to yield allocative inefficiency. More specifically, the level of industrial waste treatment turns out to be too low, i.e. entrepreneurs pay less for waste abatement than what would be their appropriate share according to the polluter-pays-principle. But irrespective of how the costs of maintaining a satisfactory water quality standard are to be shared it is the allocative displacement effect that should be emphasized, namely that the total cost of water quality remains unnecessarily high as long as the activity level of industrial waste treatment remains too low.

Another rather unexpected result relates to relative labor intensities in production. Suppose, an efficient regime with politically determined water quality standards has been implemented (Section 2), and it has been decided to raise the prevailing water quality standard. Common sense would suggest to adjust to this new standard by increasing the real price for assimilative services. But if water quality is more labor intensive in its production than the consumption good, it turns out that the price of assimilative services (in terms of labor) must be lowered. This observation reinforces the conclusion that general equilibrium analysis may yield counter intuitive results and that thorough empirical information about the relevant ecological-technological properties of the assimilation function is a crucial precondition for successful water quality management.

In many countries cost covering user charges are firmly rooted both in the history and law of public administration, in particular in the case of water quality management. Our analysis shows, however, that efficiency requires purification plants to raise their industrial sewage charges to such levels that the revenues exceed the plants' operating costs. This result challenges fundamentally the rationale of the concept of cost-covering. From the viewpoint of the political economy of water quality management the abandonment of the zero-surplus principle would seem to come close to an institutional revolution. However, the experience concerning the influence of economics on environmental policy formation suggests that revolutions of this kind are not likely to be triggered by a few economic advisers.

Section 3 clarified why, in order to be efficient, water quality management should discard effluent charges altogether and rely, instead, on prices for assimilative services combined with cost-minimizing water quality production. If the price for assimilative services is politically determined in form of an industrial sewage charge, this charge must then also be taken as the proper opportunity cost for the purification plants' use of assimilative services. Since the informational requirements of this first-best strategy are not more demanding than those of all other strategies it is very hard to see as to why water management regimes have been adopted, e.g. in West Germany, that have third-best efficiency characteristics. There may be many reasons accounting for this 'policy failure', separately or in combination. Particularly relevant arguments are, in our view, (i) incomplete or wrong information about the allocative impact of water quality strategies combining effluent charges and zero-surplus constraints, (ii) public choice considerations and (iii) unsurmountable institutional constraints.

It was also shown in Section 3 that earmarking of effluent charge revenues for purification is not a recommendable strategy from the viewpoint of economic efficiency. Even though efficiency may be slightly enhanced under some special conditions the public subsidy for purification plants under the zero-surplus constraint definitely diminishes efficiency. Earmarking is not recommendable because it implies a public subsidy for at least one region. It is well-known, of course, that in the political arena efficiency is not always the dominant argument. If, for example, dispensing with public funds would imply the reduction of water quality standards, then it makes sense for groups supporting high water quality to foster public subsidies. It is also obvious that earmarking helps these groups to achieve their goal for at least two reasons: Earmarking satisfies the polluter-pays principle (in a broad sense) — which is widely perceived as a principle of fairness — and it has the additional advantage of avoiding the annual competition for securing funds from the general public budget.

An important implication of our analysis in Section 4 is that the appropriate organization of water management depends heavily on the nature of the "ecological technology" regarding assimilative services, the size of water protection areas and both the quantity and quality of raw water. Since this empirical relationship is not yet well understood, we scrutinized two alternative hypotheses, both of which may claim some a priori plausibility. It turned out that in case of non-convex technology the water sector should be managed as a public enterprise or regulated private monopoly. Under both technological hypotheses it is shown that raw water may but need not be a scarce natural resource. A positive rent for raw water is likelier, the larger the demand for drinking water, the greater the economy's labor endowment, and the smaller the country in terms of its overall land endowment.

To understand this result recall that water as such was assumed to be abundant. But drinking water could only be generated by raw water stemming from water protection areas. The land reserved for water protection has opportunity costs which are sufficient to render raw water scarce, if water pollution does not spill over into the water protection area. However, the production costs of drinking water increase with diminishing quality of raw water. Therefore, it may pay to enlarge the water protection area for the purpose of raising raw water quality. As a by-product of the extension of the water protection area, the quantitative supply of raw water may increase so strongly that not all of it is needed to satisfy the demand for drinking water. In this case raw water does not carry an economic rent.

The principal message of Section 4 is that in order to price drinking water efficiently one must take into account that raw water quality and possibly raw water itself are scarce goods. As a policy implication our analysis demands the water works to set prices for drinking water well above their average operating costs. Such a mark-up on average operating costs is required for the sake of efficiency to reflect the scarcity of both raw water quality and (possibly) raw water quantity. It is, however, a difficult undertaking of empirical research to find out whether and to what extent raw water is scarce in its quantitative dimension.

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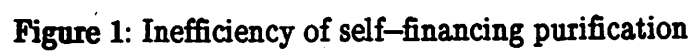


Figure 1: Inefficiency of self-financing purification

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