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Water and Economic Growth

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Water and Economic Growth

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ABSTRACT

Water and Economic Growth

Edward B Barbier

Several hydrological studies forecast a global problem of water scarcity. This raises the question as to whether increasing water scarcity may impose constraints on the growth of countries. The influence of water utilization on economic growth is depicted through a growth model that includes this congestible public good as a productive input for private producers. Growth is negatively affected by the government's appropriation of output to supply water but positively influenced by the contribution of increased water use to capital productivity, leading to an inverted-U relationship between economic growth and the rate of water utilization. Cross-country estimations confirm this relationship and suggest that for most economies current rates of freshwater utilization are not yet constraining growth. However, for a handful of countries, moderate or extreme water scarcity may affect economic growth adversely. Nevertheless, even for water-scarce countries, there appears to be little evidence that there are severe diminishing returns to allocating more output to provide water, thus resulting in falling income per capita. These results suggest caution over the claims of some hydrological-based studies of a widespread global "water crisis".

Keywords: Congestible public goods, cross-country regressions, economic growth, freshwater, water scarcity.

JEL classification: H41, O13, O41, Q25

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Introduction

Recent hydrological projections of the world's freshwater resources have pointed to an emerging global threat, the dwindling supply of freshwater relative to the growing demand for water worldwide (Falkenmark *et al.* 1998; Revenga *et al.*2000; Vörösmarty *et al.* 2000). According to various scenarios, water scarcity is expected to grow dramatically in some regions as competition for water increases between agricultural, urban and commercial sectors. The cause of this global water crisis is largely the result of population growth and economic development rather than on global climate change (Vörösmarty *et al.* 2000).[1]

Any contribution that economics can make to the current hydrological debate over the future "water crisis" must be to examine the claim that increasing water scarcity may reduce the per capita income of countries. This is the issue addressed by the following paper.

Modeling the relationship between water use and economic growth in an economy requires first determining what type of economic good is water. Although in some economies there is increasing reliance on the involvement of the private sector in providing some water services, with little loss of generality, one can and view the aggregate supply of water utilized by a country as a government-provided public good subject to congestion.[2] Following the approach of Barro (1990) and Barro and Sala-I-Martin (1992), modeling the influence of water utilization on economic growth allows the development of a growth model that includes publicly provided goods that are subject to congestion as a productive input for private producers in an economy.[3]

If water has the characteristic of a public good subject to congestion, then there are essentially two ways in which water scarcity may affect economic growth. First, as water becomes increasingly scarce in the economy, the government must exploit less accessible sources of freshwater through appropriating and purchasing a greater share of aggregate economic output, in terms of dams, pumping stations, supply infrastructure, etc. Second, it is also possible that water utilization in an economy may be restricted by the absolute availability of water. Thus the influence of water use on growth may be different for a water-constrained economy. As a consequence, in our model we distinguish between the case in which water is not a binding constraint in the economy and the case in which it is binding.

In the interior solution with no absolute water scarcity constraint, our model suggests that there is a concave, or inverted-U, relationship between growth and the rate of water utilization. The socially efficient rate of water utilization also ensures that the per capita growth rate is at its maximum. For the water-constrained economy, if too high a proportion of output is allocated to provide water, then the negative effects of allocating more output to obtain the extra water will exceed any gains in productivity. The result is that the economy will decline.

Our theoretical model therefore suggests two testable propositions. First, is there any empirical evidence of an inverted-U relationship between economic growth and the rate of water utilization for a broad cross-section of countries? Second, does the presence of moderate or extreme water scarcity adversely affect economic growth in some countries?

The empirical results of this paper provide strong support for the hypothesized inverted-U relationship between economic growth and the rate of water utilization across countries. Estimations of this relationship also suggest that current rates of freshwater utilization in the vast majority of countries are not yet constraining economic growth. To the contrary, there is probably scope for many countries to increase freshwater use – provided it is done efficiently - and still achieve higher growth rates. However, our empirical analysis also suggests that, for a handful of countries, it is difficult to reject the hypothesis that the presence of moderate or extreme water scarcity adversely affects economic growth. Nevertheless, even for water-scarce countries, there appears to be little evidence that there are severe diminishing returns to allocating more output to provide water, thus resulting in falling income per capita. Thus the results of this paper suggest caution over the claims of some hydrological-based studies that by 2025 at least 17 countries are likely to face "absolute" water scarcity, and an additional 24 countries may face "economic" water scarcity (Cosgrave and Rijsberman 2000; Seckler *et al*. 1999).[4]

The paper is organized as follows. The next section develops the approach for incorporating water as a publicly provided but congestible good in a growth model. The model is then applied to the case in which water scarcity is binding and the case in which water availability is a constraint on the economy. Using a cross-country data set, we then test the hypotheses that there is an inverted-U relationship between growth and water utilization and that water scarcity may affect this relationship adversely. The conclusion summarizes the main findings and results of the paper, and discusses recent institutional innovations that may improve the efficiency of water use in economies.

A Model of Water Use and Economic Growth

The most common measure of aggregate freshwater availability employed by hydrologists is the FAO's definition of a country's total renewable water resources, which consists of adding up average annual surface runoff and groundwater recharge from endogenous precipitation, and typically includes surface inflows from other countries (Faurés 2001; Gleick 1998 and 2000).[5] In the following analysis, we will use this flow indicator as our measure of the total renewable freshwater resources of a country.

Hydrologists also distinguish two concepts of water use: water withdrawal and water consumption (Gleick 2000, p. 41). Withdrawal refers to water removed or extracted from a freshwater source and used for human purposes (i.e. industrial, agricultural or domestic water use). However, some of this water may be returned to the original source, albeit with changes in the quality and quantity of the water. In contrast, consumptive use is water withdrawn from a source and actually consumed or lost to seepage, contamination, or a "sink" where it cannot economically be reused. Thus water consumption is the proportion of water withdrawal that is "irretrievably lost" after human use. For example, in 1995 total global freshwater withdrawals amounted to 3,800 km^3, of which 2,100 km^3 was consumed.

In this study, we will use average annual water withdrawals (km^3/year) as our measure of freshwater utilization. There are two reasons for this. First, the available data across a broad range of countries is much more reliable and accurate for water withdrawals than consumption. Second, hydrologists' measures of water stress and scarcity are usually couched either in terms of water availability per person (cubic meters per person per year) or in terms of relative water demand (the ratio of water withdrawals to total freshwater resources per year).[6] When the latter measure is employed, hydrologists typically consider values for a country between 0.2 and 0.4 to indicate medium to high water stress, whereas values greater than 0.4 reflect conditions of severe water limitation (Cosgrove and Rijsberman 2000; Vörösmarty *et al.* 2000). In the following analysis, we also consider relative water demand, or what we prefer to term the *rate of water utilization relative to freshwater availability*, to be the critical indicator.

Let w be the annual per capita renewable freshwater resources of a country (in cubic meters per person per year), and let r be total per capita freshwater utilization by that country (in cubic meters per person per year). In essence, w represents the hydrologists' concept of the total annual water supplies available to an economy on a per capita basis, whereas *r* is the actual supply provided and used, i.e. the water withdrawal.

As suggested by Barro (1990) and Barro and Sala-I-Martin (1992), the actual supply of water withdrawn and utilized by a country, for domestic, agricultural and industrial purposes, has the characteristics of a government-provided public good subject to congestion. That is, modeling the influence of per capita water withdrawal, *r*, on the growth of the economy can be depicted through a growth model that includes this congestible public good as a productive input for private producers.

The contribution of water utilization or withdrawal, *r*, to the per capita output of the i^{th} producer, y_i, can therefore be represented as

$$y_i = Ak_i f\left(\frac{r}{y}\right), \quad f' > 0,\ f'' < 0. \tag{1}$$

Following Rebelo (1991), part of private production depends on constant returns to the per capita capital stock available to the producer, k_i, which is broadly defined to include both physical and human capital components, and $A > 0$ is a parameter reflecting the level of technology. In addition, production increases with respect to the amount of water utilization, which is supplied through public services. However, because of congestion, the flow of water available to the i^{th} producer is necessarily limited by the use of water by all producers in the economy.[7] Denoting aggregate per capita output across all *N* producers in the economy as $y = Ny_i$, it follows that water utilization, *r*, has to increase relative to *y* in order to expand the water available to the i^{th} producer. In contrast, an increase in per capita output relative to total water utilization in the economy lowers the water available to each producer, and therefore reduces y_i in (1).

Not only may the aggregate water supplies in an economy have the characteristic of a public good subject to congestion but also the provision of these supplies may be affected by the physical availability of these supplies, or *water scarcity*. There are two ways in which this may occur.

First, it can be generally assumed that the government provides water for use in the economy by appropriating a share of aggregate private output. For example, in modeling the supply of general public goods, Barro (1990) has argued that one can think of government simply purchasing a flow of output from the private sector (e.g. battleships and highways), the services of which the government in turn makes available to the economy as a whole. In order to provide the water utilized by the economy, r, one can also envision the government purchasing or appropriating a share, z, of aggregate economic output that is specifically devoted to water supply (e.g., dams, irrigation networks, water pipes, pumping stations, etc.). This suggests that $r = zy$. However, as per capita freshwater utilization in the economy, r, rises relative to the available annual per capita annual renewable freshwater resources, w, one would also expect that more aggregate output must be allocated for water supply. As water becomes increasingly scarce, i.e. water utilization rises relative to available freshwater resources, the government must exploit less accessible sources of freshwater. To do this, requires appropriating and purchasing a greater share of aggregate economic output, in terms of dams, pumping stations, supply infrastructure, etc. Denoting $\rho = r/w$ as the *rate of water utilization relative to total freshwater availability*, it therefore follows that

$$r = z(\rho)y, \quad z' > 0, z'' > 0, z(0) = 0, z'(0) = 0, z(1) = \alpha, z'(1) = \beta < \infty, \qquad (2)$$

where $\beta > 0$, $0 < \alpha < 1$, and $z(\rho) < 1$ is the proportion of aggregate economic output appropriated by the government for providing water, which is assumed to be an increasing function of the rate of water utilization by the economy relative to its freshwater resources, ρ. In addition, as aggregate output, y, rises in the economy, so does water utilization, r. Finally, as water becomes increasingly scarce, i.e $\rho \to 1$, the proportion of output appropriated by the government to supply water is bounded above by α, and the rate of appropriation by β.[8]

Water scarcity also influences water utilization in an economy by limiting the total amount of water available for withdrawal. That is, even if all freshwater resources are used (i.e. $\rho = 1$), water withdrawals are finite. Thus total per capita freshwater availability imposes the following constraint on the economy

$$r = z(\rho)y \leq w, \tag{3}$$

with $r = z(\rho) < w$ if $0 \leq \rho < 1$ and $r = z(\rho) = w$ if $\rho = 1$.

Making the standard assumption that the supply of labor and population are the same, and that population grows at the constant rate n, per capita output in the economy is allocated as

$$y = c + r + \dot{k} + (\omega + n)k, \ \ k(0) = k_0, \tag{4}$$

where c is per capita consumption, $\dot{k}$ is the change in the per capita capital stock over time and ω is the rate of capital depreciation.

Finally, all consumers in the economy are assumed to share identical preferences over an infinite time horizon, given by

$$W = \int_0^\infty e^{-\delta t}\left[\frac{c^{1-\theta}-1}{1-\theta}\right]dt, \quad \delta = \upsilon - n \geq 0, \tag{5}$$

where υ is the rate of time preference. Maximization of W with respect to choice of c and ρ, subject to (1) to (4), yields the following Lagrangian expression

$$L = \frac{c^{1-\theta}-1}{1-\theta} + \lambda\left[(1-z(\rho))Akf(z(\rho)) - c - (\omega+n)k\right] + \mu\left[w - z(\rho)Akf(z(\rho))\right]. \tag{6}$$

The resulting first-order conditions are

$$c^{-\theta} = \lambda \tag{7}$$

$$\begin{aligned} &\lambda\left[(1 - z(\rho))Akf'z'\right] - \lambda Akf(z(\rho))z' = \mu\left[Akf(z(\rho))z' + z(\rho)Akf'z'\right], \\ &\mu(t) \geq 0,\ w - z(\rho)Akf(z(\rho)) \geq 0,\ \mu\left[w - z(\rho)Akf(z(\rho))\right] = 0. \end{aligned} \tag{8}$$

$$\dot{\lambda} = \delta\lambda - \lambda\left[1 - z(\rho)Af(z(\rho)) - (\omega + n)\right] + \mu z(\rho)Af(z(\rho)) \tag{9}$$

$$\lim_{t\to\infty}\left\{e^{-\delta t}\lambda(t)k(t) = 0\right\}. \tag{10}$$

plus the equation of motion (4). Equation (7) is the standard condition that the marginal utility of consumption equals the shadow price of capital, λ. Equation (8) determines the optimal allocation of the rate of water utilization of the economy, including the complementary slackness condition imposed by the water scarcity constraint. The Lagrangean multiplier μ can be interpreted as the scarcity value of freshwater supplies to the economy. Equation (9) indicates the change over time in the value of the capital stock of the economy. Finally, equation (10) is the transversality condition for this infinite time horizon problem.

Differentiating (7) with respect to time and substituting into (9) yields

$$g = \frac{\dot{c}}{c} = \frac{1}{\theta}\left[(1 - z(\rho))Af(z(\rho)) - (\omega + n + \delta) - \mu\frac{z(\rho)Af(z(\rho))}{c^{-\theta}}\right]. \tag{11}$$

The above equation indicates that growth in per capita consumption is negatively affected by the government's appropriation of output to supply water, $1 - z(\rho)$, positively influenced by the contribution of water use to the net marginal productivity of capital, $Af(z(\rho)) - (\omega + n + \delta)$, and adversely impacted by conditions of water scarcity, $\mu\, z(\rho)Af(z(\rho))/c^{-\theta}$.

Further interpretation of the influence of water use on growth in the economy requires examining the conditions under which the water scarcity constraint (3) is binding or not. We begin with the interior solution in which the economy is not constrained by per capita freshwater availability.

Case 1. Water Scarcity Is Not Binding in the Economy

If the water scarcity constraint (3) is not binding, then the complementary slackness condition requires that $w > r$ and $\mu(t) = 0$ for all t. For this interior solution, equation (11) reduces to

$$g = \frac{1}{\theta}\left[(1 - z(\rho))Af(z(\rho)) - (\omega + n + \delta)\right]. \tag{12}$$

Although water scarcity no longer affects the growth in per capita consumption, g is still influenced by water utilization in the economy. Growth is negatively affected by the government's appropriation of output to supply water, $1 - z(\rho)$, and positively influenced by the contribution of water use to the net marginal productivity of capital, $Af(z(\rho)) - (\omega + n + \delta)$. Moreover, it can be easily demonstrated that in this economy per capita consumption, capital and output all grow at the same rate g, and there are no transitional dynamics to this steady-state growth path.[9] In the initial period, the socially efficient level of water use, ρ^*, that satisfies (8) for $\mu(0) = 0$ is chosen, along with the initial values for per capita consumption and output. After the initial period, $k(t)$, $c(t)$ and $y(t)$ then grow at the constant rate determined by (12).

It is also straightforward to demonstrate that the socially efficient rate of water utilization, ρ^*, maximizes growth in the economy. Differentiating (12) with respect to ρ we get

$$\frac{\partial g}{\partial \rho} \; \begin{matrix} > \\ = \\ < \end{matrix} \; 0 \quad \text{if} \quad f(z(\rho)) \; \begin{matrix} < \\ = \\ > \end{matrix} \; (1 - z(\rho))f'(z(\rho)). \tag{13}$$

Thus the socially efficient rate of water utilization that satisfies (8) also ensures that the per capita growth rate is at its maximum, g^*.[10] Moreover, as $z(\rho)$ is strictly convex, it follows that the slope of (12) with respect to the rate of water utilization is positive for $\rho < \rho^*$, and conversely, is negative for $\rho > \rho^*$. Consequently, as depicted in Figure 1, the relationship between growth and the rate of water utilization is concave.

However, current policies for supplying water in most countries, even those that do not face binding water scarcity constraints, are not socially efficient (Dosi and Easter 2000). For example, it is possible that water management in some countries may lead to a rate of water utilization that is too high, i.e. $\rho^0 > \rho^*$. There are two implications of this outcome. First, as is clear from Figure 1, over-use of water will lead to a lower rate of economic growth, i.e. $g^0 < g^*$. Second, individual producers that benefit for the provision of water are not "contributing" a sufficient share of the social costs of providing this public good.

A lower rate of economic growth, i.e. $g^0 < g^*$, may also result if the rate of water utilization is too low, i.e. $\rho^1 < \rho^*$. An economy in this situation may be able to increase its growth by utilizing more of its freshwater resources.

Case 2. The Water-Constrained Economy

We now turn to the case where the water scarcity constraint (3) is binding in the economy, and thus the complementary slackness condition requires that $w = r$ and $\mu(t) > 0$ for all t. Equation (2) also implies that $z(1) = \frac{r}{y} = \frac{w}{y} = \alpha,\ z'(1) = \beta < \infty$. That is, the proportion of aggregate economic output appropriated by the government for providing water is now determined by the ratio of the potential water supplies to aggregate output, which is bounded by the maximum rate of appropriation, α.

For the water-constrained economy, growth in per capita consumption is now governed by a modified version of equation (11), with the rate of output appropriated by the government to supply water set at the maximum rate, α

$$g_S = \frac{\dot{c}}{c} = \frac{1}{\theta}\left[(1-\alpha)Af(\alpha) - (\omega + n + \delta) - \mu\frac{\alpha A f(\alpha)}{\lambda}\right]. \tag{14}$$

Growth in the water-constrained economy, g_S, is positively influenced by the net marginal productivity of capital, $Af(\alpha) - (\omega + n + \delta)$, including the contribution of water use to this productivity, but adversely affected by the government's appropriation of output to supply water, $1 - \alpha$, and by the conditions imposed by water scarcity, $\mu\alpha Af(\alpha)/\lambda$. Note as well that, in a water-constrained economy, it is always optimal for the government to choose the maximum rate of appropriation of output to supply freshwater.[11]

For the water-constrained economy, condition (8)

becomes $\mu = \lambda\left[\frac{f'(\alpha)}{f(\alpha)+\alpha f'(\alpha)} - 1\right] > 0$. [12] Using the latter expression, (14) can be simplified

further to

$$g_S = \frac{1}{\theta}\left[Af(\alpha) - (\omega + n + \delta) - \alpha A f(\alpha)\left(\frac{f'(\alpha)}{f(\alpha)+\alpha f'(\alpha)}\right)\right]. \tag{15}$$

Again, it is straightforward to show that in the water-constrained economy, per capita consumption, capital and output all grow at the same rate g_S as governed by (15). [13] In the initial period, the government chooses the maximum rate of appropriating economic output in order to supply freshwater, $\alpha y = r = w$, along with the initial values for per capita consumption and output. After the initial period, $k(t)$, $c(t)$ and $y(t)$ grow at the constant rate determined by (15).

Although in a water-constrained economy it is always optimal for the government to appropriate output at the maximum rate, α, to supply freshwater, this does not necessarily mean that economic growth will occur. From (15),

$$g_S \overset{>}{\underset{<}{=}} 0 \qquad \text{if} \qquad Af(\alpha) - (\omega + n + \delta) \overset{>}{\underset{<}{=}} \alpha A f(\alpha)\frac{f'(\alpha)}{f(\alpha) + \alpha f'(\alpha)} \ . \tag{16}$$

That is, growth in the water-constrained economy will occur only if the net marginal productivity of capital exceeds the negative effects on the economy of water scarcity.

In sum, in the water-constrained economy, water is always valuable in the sense that the marginal benefits of water in terms of its contribution to marginal productivity will always exceed the social cost of supply. This means that it is always optimal to allocate the maximum amount of output possible to extract the available freshwater supplies. However, whether this leads to growth or economic decline depends on whether the gains in net marginal productivity outweigh the resource costs to the economy of providing this water. An economy that has either too little or too much water relative to economic output is likely to be more adversely affected by this decision than an economy that has moderate supplies relative to overall output. The latter water-constrained economy can still provide sufficient water supplies to all its producers in order to increase net marginal productivity in the economy without allocating too much output to do so, and thus achieve economic growth.

Cross-Country Empirical Analysis of Water and Growth

The above theoretical analysis of the relationship between growth and water utilization suggests the possibility of a concave, or "inverted-U", relationship (see equation (13) and Figure 1). That is, as the rate of water utilization, ρ, in an economy increases, economic growth, *g*, first increases, then stabilizes and eventually falls. This is the normal case that we would expect for an economy in which water availability is not an absolute binding constraint.

This suggests a simple test for examining the relationship between water use and growth across countries; i.e., is there any empirical evidence of an inverted-U relationship between economic growth and the rate of water utilization for a broad cross-section of countries? The rest of this section summarizes one approach to testing this hypothesis through a cross-country analysis.

The key variable in this analysis is of course the rate of water utilization, ρ. A recent assessment of the world's freshwater supplies provides estimates of the annual renewable water resources and the total amount of freshwater withdrawal for a single year of estimate for 163 countries (Gleick 1998 and 2000). The ratio of freshwater withdrawals, r, relative to supplies, w, can therefore serve as our cross-country measure of $\rho = r/w$. However, the *World's Water* database reports only a single-year estimate of freshwater withdrawals and supplies for each country. In addition, because different sources are used to provide these estimates, the year in which r and w is estimated varies greatly from country to country. Given these limitations, it is therefore possible to estimate a cross-country relationship between economic growth and ρ through cross-sectional as opposed to pooled cross-sectional and time series (i.e. panel) analysis.

In empirically examining the hypothesized the inverted-U relationship between g and ρ, one must also be aware of several issues raised in the general literature on estimating cross-country growth relationships (see Agénor (2000) and Temple (1999) for recent reviews). First, most researchers generally have opted for the five or ten-year averages of annual growth rates in order to avoid any business cycle effects. Given that many of our single-year estimates of ρ for many countries are from the mid-1990s, this necessarily limits us to representing growth as a five-year annual average. Second, to avoid simultaneity concerns, researchers often make use of initial values for the explanatory variables in the growth regressions. For example, if the single-year estimate of the rate of water for a country in our sample is, say, for 1994, then for this country we should regress the average annual growth over 1994-9 on the value of ρ for this country in 1994. Finally, because cross-sectional growth regressions require assumptions about parameter constancy, whereas in reality countries differ widely in terms of social, political and institutional characteristics, the resulting neglect of possible parameter heterogeneity in cross-sectional models is likely to result in problems with heteroskedasticity. The result is that most researchers use heteroskedastic-consistent standard errors, or alternative techniques, to correct for the observed heteroskedasticity.

Taking the above considerations into account, the following basic empirical specification can be used to test the hypothesis that there is an inverted-U relationship between growth and the rate of water utilization across countries:

$$g_{t,t+5} = b_0 + b_1\rho_t + b_2\rho_t^2 + \mu \tag{17}$$

where the dependent variable is the five-year average growth rate for each country, beginning at the year of estimate, t. Note that $b_1 > 0$ and $b_2 < 0$ implies that the inverted-U hypothesis holds.

The empirical literature on growth has also identified a substantial number of variables that are partially correlated with the rate of economic growth across countries. The problem faced by this literature is that growth theories are often not explicit enough about which variables should belong in a "true" regression of growth. Recent efforts have therefore focused on determining "robust" empirical estimations of proposed growth relationships (Levine and Renelt 1992; Sala-I-Martin 1999). The general approach is to argue that there is a vector of "fixed" explanatory variables that are widely used in the literature and that have to be somewhat robust in the sense that they systematically seem to matter in most growth regressions. It therefore follows that, if other variables are also thought to explain growth rates across countries, then these variables should add to rather than detract from the robustness of the regression. That is, the inclusion of these additional variables in growth regressions along with the "fixed" variables should not affect the robustness of the latter, and the new variables should in themselves be significantly correlated with growth.

The implication for our model is that, if the hypothesized U-shaped relationship between growth and the rate of water utilization is robust, then this relationship should also hold if the normal set of "fixed" variables, $\boldsymbol{x}$, that account for growth across countries is also included. We therefore also estimate the following basic growth regression:

$$g_{t,t+5} = b_0 + b_1\rho_t + b_2\rho_t^2 + \boldsymbol{b}_x\boldsymbol{x} + \mu\ . \tag{18}$$

Following Sala-I-Martin (1999) and Temple (1999), we choose the "fixed" variables, **x**, to be the initial level of income per capita in year *t*, the primary-school enrollment rate in year *t* and the secondary-school enrollment rate in year *t*.[14]

Finally, the empirical literature on growth has also identified consistently a number of other variables that appear to be significantly correlated with growth across countries. Of particular importance appear to be variables that reflect the institutional framework, the level of development and the degree of trade openness of countries (Agénor (2000), Keefer and Knack (1997), Sachs and Warner (1995) and (1997); Sala-I-Martin (1999) and Temple (1999)). This suggests that, extending our growth model further to include these additional explanatory variables, $\boldsymbol{y}$, should not affect the hypothesized U-shaped relationship between growth and the rate of water utilization, if that relationship is robust. Our full growth model for empirical estimation is:

$$g_{t,t+5} = b_0 + b_1\rho_t + b_2\rho_t^2 + \boldsymbol{b_x x} + \boldsymbol{b_y y} + \mu\ , \tag{19}$$

where ***y*** includes, for each country in the sample, an index of political stability/lack of political violence, an index of the control of corruption, the annual population growth rate in year *t*, total trade as a percentage of real GDP in year *t* and a dummy variable indicating whether the country is classified as a developing economy.

The data for the five-year average cross-country growth rates, *g*, and the various variables comprising ***x*** and ***y*** were all derived from the World Bank *World Development Indicators* data set (World Bank 2001). The exceptions were the control of corruption and political stability indices, which were derived from the World Bank's study of governance across countries (Kaufmann *et al.* 1999a and 1999b), and the dummy variable for developing countries, which uses the UN Food and Agricultural Organization classification of countries.[15]

Table 1 summarizes the growth regression results for equations (17), (18) and (19). As the Wald statistic and Breusch-Pagan Lagrange multiplier tests imply, all models required correction either for multiplicative heteroskedasticity using maximum likelihood estimation or for generalized heteroskedasticity using White's consistent estimator.

For all three models, the coefficients b_1 and b_2 not only have the expected signs but also display consistently similar magnitudes. In the basic and full growth models, for those additionally included variables that are statistically significant in explaining growth, their estimated coefficients also conform to the predicted signs.[16] Overall, the three regression models suggest that the hypothesis of an inverted-U relationship between growth and the rate of water utilization across the diverse group of countries in our sample cannot be rejected, as this relationship appears to be remarkably robust.

For each of the models in Table 1 an estimate of ρ* is computed, which corresponds to an estimate of the rate of water utilization that leads to maximum economic growth as indicated in Figure 1. The estimated ρ* is fairly large across the three models, ranging from 2.9 to 3.8. However, these estimated values must be treated with caution. Only a handful of countries in our full sample of 163 countries show rates of water utilization at or exceeding these levels[17] The vast majority of countries display rates of water utilization that are much less than one. For example, the mean of ρ in the full sample is 0.548, whereas the median is only 0.047. In essence, the data are allowing us to estimate only the part of the curve depicted in Figure 1 well to the left of ρ*. Thus although these clustered observations appear to fit the hypothesized inverted U-shaped relationship, any computed value of ρ* is essentially a projection of this estimated relationship that is likely to be far less accurate given that so few actual observations are available to verify this projection.

Table 1 also reports the elasticity estimates for ρ. These are fairly consistent, ranging from 0.3-0.35 across the three models. This suggests that, on average, the countries in each sample could increase freshwater utilization and achieve a modest increase in growth. For example, the full growth model predicts that an increase in the rate of water utilization by 10% could increase the average growth rate in the sample of countries from 1.30% to 1.33%.

In sum, the regression results reported in Table 1 provide strong support for the hypothesized inverted-U relationship between economic growth and the rate of water utilization across countries. Our estimations of this relationship also suggest that current rates of freshwater utilization in the vast majority of countries are not constraining economic growth. To the contrary, most countries may be able to increase growth by utilizing more of their freshwater resources, although there are obvious limits on how much additional growth can be generated in this way.

The latter caveat is extremely important. Even if a country could raise its growth rate by increasing its rate of water utilization, maintaining ρ greater than one is likely to be unsustainable for most countries over the long run. In fact, as our theoretical model indicates, for an economy in which water scarcity is binding, i.e $w = r$ and therefore $\rho = 1$, the resulting scarcity constraint will have very different implications for the economy's growth path (compare equations (12) and (15)). Economic growth is now determined by the ratio of the potential water supplies to aggregate output, which is equal to the maximum rate of government appropriation, i.e. $w/y = \alpha$. As condition (16) indicates, although in a water-constrained economy it is always optimal for the government to appropriate output at the maximum rate, α, to supply freshwater, this does not necessarily mean that economic growth will actually occur. For the economy to grow requires, firstly, that the net marginal productivity of capital exceeds the negative effects on the economy of water scarcity, and secondly, that there are sufficient freshwater resources, w, available to appropriate.

Empirically verifying condition (16) and the growth path of the water-constrained economy is very difficult for our data set. First, only ten out of the 163 countries in our sample display rates of water utilization of $\rho \geq 1$. This is too small a sub-sample for conducting a separate regression.[18] Second, as noted above, our data set contains only a single-year estimate of the rate of water utilization for each country. Some countries that have rates of water utilization of $\rho \geq 1$ in a single year may not necessarily experience chronic water scarcity over a longer period of time, as implied by our model of the water-constrained economy.

Nevertheless, provided that we can use an appropriate indicator of long-run water scarcity across countries, it may be possible to test an alternative hypothesis, namely that growth rates are likely to be adversely affected in economies facing chronic water scarcity.

Hydrologists have suggested that one potential indicator of long-run water scarcity is the so-called "Falkenmark water stress index" (Falkenmark 1989; Falkenmark and Rockström 1998). The water stress index is constructed by taking a past level of renewable freshwater supply available to a country (e.g. from the 1960s to early 1990s) and dividing it by that country's population at a future date, usually in 2000 and 2025. While a country with more that 1,700 cubic meters per year per person is expected to experience only intermittent and localized water shortages, the threshold of 1,000 cubic meters is considered to be a level below which a country is likely to experience widespread and chronic shortfalls. At less than 500 cubic meters per capita annually, water availability can be considered to be so serious a problem that social and economic development may be threatened.

It is possible to devise a water stress index for our sample of 163 countries, using the single-year estimate of freshwater supply for each country divided by its population in year 2000.[19] Sixteen countries face conditions of extreme water scarcity (less than 500 cubic meters/person/year), whereas four countries experience moderate water scarcity (between 500 and 1,000 cubic meters/person/year). By including dummy variables to represent the moderate and extreme water scarcity countries, respectively, in the regressions of equations (17), (18) and (19), we can test the hypothesis that conditions of scarcity may affect adversely economic growth rates across countries.

Table 2 summarizes the results for the regressions with the water scarcity dummies. Once again, all models required correction either for multiplicative heteroskedasticity using maximum likelihood estimation or for generalized heteroskedasticity using White's consistent estimator.

The inclusion of the water scarcity dummies in the regressions produces remarkably consistent estimations compared to the previous regressions that excluded the dummies (see Tables 1 and 2). The hypothesis of an inverted-U relationship between growth and the rate of water utilization cannot be rejected, and the estimates of the turning point for ρ and its elasticity are similar. For the full growth model that includes the moderate water scarcity dummy, a 10% increase in the rate of water utilization again raises the average growth rate in the sample of countries from 1.30% to 1.33%. For the full growth model that includes both the moderate and water scarcity dummies, a 10% increase in ρ will raise growth only slightly more, to 1.34%.

Table 2 indicates that the water scarcity dummies have the expected negative signs, although they are significant only in the full growth models and in the basic growth model in which both the moderate and extreme water scarcity dummies are included. Given the robustness of many of the additional explanatory variables in the basic and full growth models, these regressions are likely to yield more reliable estimates of growth rates across countries. Thus, based on the results of Table 2, it is difficult to reject the hypothesis that the presence of moderate or extreme water scarcity adversely affects economic growth.

Conclusion

This paper has sought to shed light on recent concerns expressed over the global "water crisis" by examining the possible linkages between water scarcity and growth through both a theoretical and empirical analysis. The approach taken was to examine the influence of the rate of water utilization on an economy in a growth model that includes this congestible public good as a productive input for private producers. We looked at two potential effects, a relative and an absolute water scarcity impact.

In the case of the economy in which there is no absolute water scarcity constraint, our model suggests that there is a concave, or inverted-U, relationship between growth and the rate of water utilization (see Figure 1). Moreover, the socially efficient rate of water utilization also ensures that the per capita growth rate is at its maximum, g^*. In contrast, over or under-use of water is likely to result in less overall growth in the economy. For the water-constrained economy, the relationship between growth and the rate of water utilization is likely to be more complex. Although it is always optimal for the government to appropriate output at the maximum rate, α, to supply freshwater, this does not necessarily mean that economic growth will occur (see equation (16)). Growth requires, firstly, that the net marginal productivity of capital exceeds the negative effects on the economy of water scarcity, and secondly, that there are sufficient freshwater resources, w, available to appropriate.

The empirical analysis of this paper provides strong support for the hypothesized inverted-U relationship between economic growth and the rate of water utilization across countries. Our estimations of this relationship also suggest that current rates of freshwater utilization in the vast majority of countries are not yet constraining economic growth. To the contrary, most countries may be able to increase growth by utilizing more of their freshwater resources – provided they do so efficiently - although there are obvious limits on how much additional growth can be generated in this way. Countries that are "water stressed", i.e. have limited freshwater supplies relative to current and future populations, may find it especially difficult to generate additional growth through more water use. Our empirical analysis suggests that we cannot reject the hypothesis that the presence of moderate or extreme water scarcity adversely affects economic growth.

There are some important caveats to these generally optimistic findings. First, freshwater supplies and use rates vary considerably across the regions within a country. A country as a whole may appear to have sufficient freshwater supplies relative to demand, but specific regions and sectors may not. Variability in climate, rainfall, demographics and economic activity may also contribute to problems of localized water scarcity. In particular, arid and semi-arid regions of the world are the most vulnerable to future water stress (Vörösmarty *et al.* 2000). Second, a critical factor in assessing the actual amount of freshwater available in a country is that many rivers, lakes, groundwater aquifers and other water bodies often cross political boundaries or are difficult to exploit for legal, technical or economic reasons (Gleick 2000).[20] Third, while water-scarcity constraints on overall economic growth may be less likely, freshwater availability could be more problematic for key sectors in some countries, such as agriculture. For example, many hydrologists, meteorologists and water resource experts have expressed concern recently that, with world population increasing by 50% over the next 30 years, water scarcity may become a key factor behind global food insecurity, reduced production growth and rising international cereal prices (Falkenmark *et al.* 1998; Rosegrant and Cai 2001; Seckler *et al.* 1999; United Nations 1997).

Finally, although in this paper it was analytically convenient to view water as a congestible public good supplied solely by a government to the private producers of an economy, it is important to note that current thinking in the economics of water management challenges the notion that a government should be the sole provider of water services in an economy. The main argument in favor of institutional reform is that, given the rapid growth of water demands over recent decades, the public sector alone is incapable of ensuring socially efficient levels of supply and water utilization in many countries (Briscoe 1996; Easter and Dosi 2000). Instead, there is a growing realization that providing an adequate supply of water to an economy and ensuring its efficient utilization constitutes a bundle of services that is best divided up between the public and private sector, with some of the services more efficiently provided by the private sector (Parker and Tsur 1997). Socially efficient water utilization is likely to require the public sector maintaining its comparative advantage in certain services, such as large-scale infrastructure investments, protecting and regulating monopoly power, controlling negative externalities such as water pollution, preventing the overuse of water resources will ill-defined or "open access" property rights, and above all as emphasized in the approach of this paper, ensuring that water as a public good is not under-provided in the economy. However, there is also considerable scope for increased involvement of the private sector, particularly through the establishment of water markets, water pricing reforms and the privatization of water utilities that supply final-use services.

Already, increased private sector participation and use of water markets and cost-recovery pricing has occurred in the United States, the European Union and even some developing countries (Easter and Dosi (2000); Johnstone and Webb (2001)). It appears that, if the rate of water utilization is to be socially efficient so as to maximize economic growth, then public as well as private sector involvement will be required as privatization, pricing reform and water markets all have the potential for establishing the incentives for more efficient use of water in the economy then simply relying on public sector water management alone.

References

Pierre-Richard Agénor. 2000. *The Economics of Adjustment and Growth*. Academic Press, San Diego.

Robert J. Barro. 1990. "Government Spending in a Simple Model of Endogenous Growth." *Journal of Political Economy* 98(5):S103-S124.

Robert J. Barro and Xavier Sala-I-Martin. 1992. "Public Finance in Models of Economic Growth." *Review of Economic Studies* 59:645-661.

Robert J. Barro and Xavier Sala-I-Martin. 1995. *Economic Growth*. McGraw Hill, New York.

John Briscoe. 1996. "Managing Water as an Economic Good: Rules for Reformers." *Water Supply* 15(4):153-172.

William J. Cosgrove and Frank R. Rijsberman. 2000. *World Water Vision: Making Water Everybody's Business.* World Water Council and Earthscan Publications, London.

Cesare Dosi and William K. Easter. 2000. "Water Scarcity: Institutional Change, Water Markets and Privatisation." *Nota di Lavoro 102.2000.* Fondazione Eni Enrico Mattei Working Paper Series, Milan, Itlay.

Malin Falkenmark. 1989. "The Massive Water Scarcity Now Threatening Africa – Why Isn't It Being Addressed?" *Ambio* 18(2):112-118.

Malin Falkenmark and Johan Rockström. 1998. "Water in Emergencies." In S. Fleming, ed. *Forum: War and Water.* International Committee of the Red Cross, Geneva, pp. 22-29.

Malin Falkenmark, Wolf Klohn, Jan Lundqvist, Sandra Postel, Johan Rockström, David Seckler, Jillel Shuval and James Wallace. 1998. "Water Scarcity as a Key Factor Behind Global Food Insecurity: Round Table Discussion." *Ambio* 27(2):148-154.

Jean-Marc Faurés, Domitille Vallée, Ăse Eliasson, Jippe Hoogeveen. 2000. "Statistics on Water Resources by Country in FAO's AQUASTAT Programme.". Paper presented at the Joint ECE/EUROSTAT Work Session on Methodological Ossues of Environmental Statistics. Ottawa, Canada, October 1-4, 2001.

Peter H. Gleick. 1998. *The World's Water 1998-1999: The Biennial Report on Freshwater Resources.* Island Press, Washington DC.

Peter H. Gleick. 2000. *The World's Water 2000-2001: The Biennial Report on Freshwater Resources.* Island Press, Washington DC.

Nick Johnstone and Libby Wood, eds. 2001. *Private Firms and Public Water: Realizing Social and Environmental Objectives in Developing Countries.* Edward Elgar, London.

Philip Keefer and Stephen Knack. 1997. "Why Don't Poor Countries Catch Up? A Cross-National Test of an Institutional Explanation." *Economic Inquiry* 35:590-602.

Daniel Kaufmann, Aart Kraay and Pablo Zoido-Lobaton. 1999a. "Aggregating Governance Indicators". World Bank Policy Research Department Working Paper No. 2195.

Daniel Kaufmann, Aart Kraay and Pablo Zoido-Lobaton. 1999b. "Governance Matters". World Bank Policy Research Department Working Paper No. 2196.

Mark W. Rosegrant and Ximing Cai. 2001. "Water for Food Production" In Ruth S. Meinzen-Dick and Mark W. Rosegrant, eds. *2020 Vision Focus 9: Overcoming Water Scarcity and Quality Constraints.* International Food Policy Research Institute, Washington, DC.

Ross Levine and David Renelt. 1992. "A Sensitivity Analysis of Cross-Country Growth Regressions." *American Economic Review* 82(4):942-963.

Douglas D. Parker and Yacov Tsur, eds. 1997. *Decentralization and Coordination of Water Resource Management.* Kluwer Academic Publishers, Dordrecht.

Carmen Revenga, Jake Brunner, Norbert Henninger, Ken Kassem and Richard Payne. 2000. *Pilot Analysis of Global Ecosystems: Freshwater Systems.* World Resources Institute, Washington, DC.

Jeffrey D. Sachs and Andrew M. Warner. 1995. "Economic Reform and the Process of Global Integration." *Brookings Papers on Economic Activity* Spring (1):1-118.

Jeffrey D. Sachs and Andrew M. Warner. 1997. "Fundamental Sources of Long-Run Growth." *American Economic Review* 87(2):184-188.

Santiago Rebelo. 1991. "Long Run Policy Analysis and Long Run Growth." *Journal of Political Economy* 99:500-521.

Xavier Sala-I-Martin. 1999. "I Just Ran Two Million Regressions." *American Economic Review* 87(2):178-183.

David Seckler, Randolph Barker and Upali Amarasinghe. 1999. "Water Scarcity in the Twenty-first Century." *International Journal of Water Resources Development* 15(1/2):29-42.

Jonathon Temple. 1999. "The New Growth Evidence." *Journal of Economic Literature* 37(March):112-156.

Charles J. Vörösmarty, Pamela Green, Joseph Salisbury and Richard B. Lammers. 2000. "Global Water Resources: Vulnerability from Climate Change and Population Growth." *Science* 289 (14 July):284-288.

United Nations 1997. *Comprehensive Assessment of the Freshwater Resources of the World*. World Meteorological Organization, Geneva.

World Bank (2001). *World Development Indicators 2001 CD-ROM*. The World Bank, Washington DC.

Figure 1. Growth and the Rate of Water Utilization for the Interior Solution

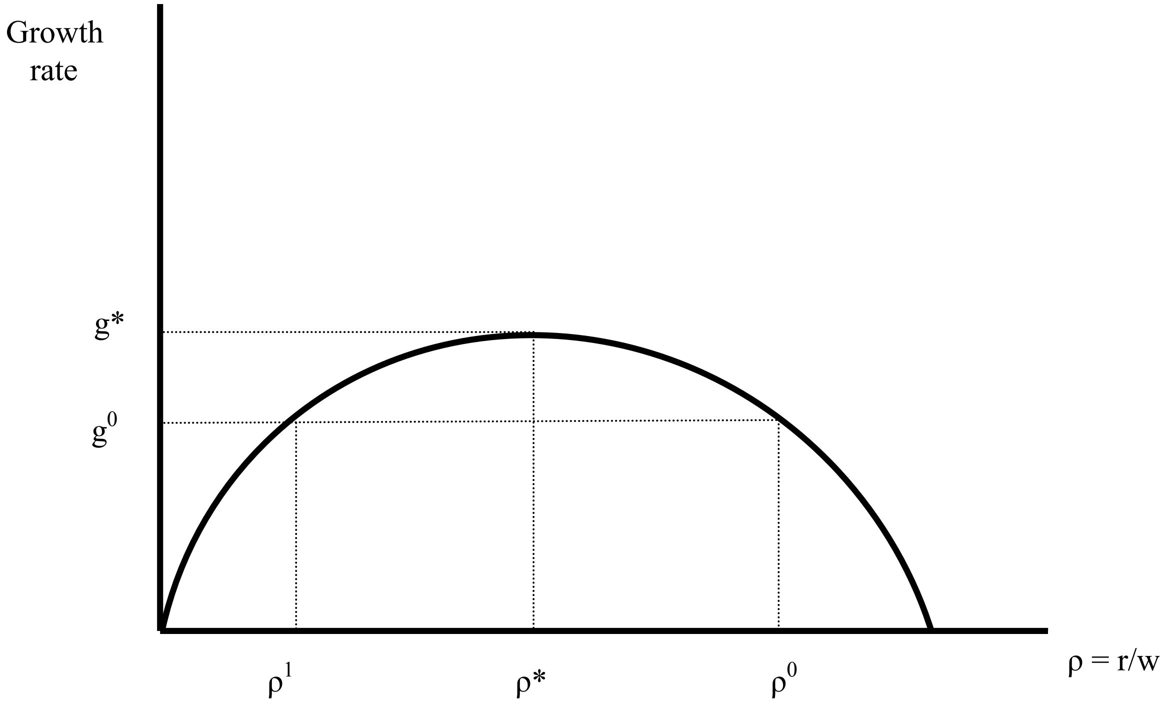

Table 1. Cross-Country Regression of Water Use and Growth

Dependent variable: Five-year average annual growth of per capita income ($g_{t,t+5}$)

Variables	**Base case model**[a]	**Basic growth model**[a]	**Full growth model**[b]
Constant	0.818	-1.275	9.569
	(2.432)*	(-0.685)	(2.534)*
ρ	1.614	1.647	1.947
	(5.117)**	(5.828)**	(2.515)*
ρ^2	-0.279	-0.273	-0.257
	(-6.815)**	(-7.024)**	(-2.577)**
Log per capita income in year *t*		-0.042	-1.538
		(-0.146)	(-3.379)**
Primary school enrollment in year *t*		0.029	0.016
		(2.138)*	(1.096)
Secondary school enrollment in year *t*		-0.005	0.009
		(-0.383)	(0.547)
Population growth in year *t*			-0.496
			(-1.748)†
Trade openness in year *t*			-0.002
			(-0.322)
Political stability indicator			1.183
			(2.421)*
Control of corruption indicator			2.454
			(3.640)**
Dummy for developing countries			2.683
			(2.258)*
Inverted-U relationship	**Yes**	**Yes**	**Yes**
(Estimate of ρ^*)	(2.895)	(3.025)	(3.790)
Elasticity of ρ	**0.292**	**0.270**	**0.348**
(Sample mean of ρ)	(0.227)	(0.229)	(0.248)
(Sample mean of $g_{t,t+5}$)	(1.155)	(1.294)	(1.298)
Number of observations (*N*)	*N* = 143	*N* = 132	*N* = 120
Wald statistic	99.500**	88.110**	104.799**
Breusch-Pagan LM statistic	1.743	2.936	32.831**

Notes: [a] Maximum likelihood estimation after correcting the variance-covariance matrix for multiplicative heteroskedasticity. *t*-statistics are in parentheses.

[b] Ordinary least squares employing standard errors based on White's heteroskedasticity-consistent variance-covariance matrix.

**Significant at 1% level. *Significant at 5% level. †Significant at 10% level.

Table 2. Cross-Country Regression of Water Use and Growth: Controlling for Moderate and Extreme Water Scarcity

Dependent variable: Five-year average annual growth of per capita income ($g_{t,t+5}$)

Variables	Moderate Water Scarcity			Moderate and Extreme Water Scarcity		
	Base case model[a]	**Basic growth model**[a]	**Full growth model**[b]	**Base case model**[a]	**Basic growth model**[a]	**Full growth model**[b]
Constant	0.848	-1.264	9.652	0.826	-3.508	9.567
	(2.461)*	(-0.683)	(2.553)*	(2.395)*	(-2.118)*	(2.534)*
ρ	1.602	1.652	1.939	1.917	3.404	2.100
	(5.048)**	(5.895)**	(2.509)*	(3.250)**	(9.750)**	(2.015)*
ρ^2	-0.278	-0.275	-0.255	-0.310	-0.466	-0.273
	(-6.766)**	(-7.135)**	(-2.565)**	(-4.964)**	(-11.192)**	(-2.183)*
Log per capita income in year *t*		-0.034	-1.550		0.375	-1.542
		(-0.120)	(-3.400)**		(1.450)	(-3.342)**
Primary school enrollment in year *t*		0.031	0.017		0.040	0.017
		(2.305)*	(1.125)		(3.069)**	(1.125)
Secondary school enrollment in year *t*		-0.009	0.009		-0.040	0.008
		(-0.656)	(0.535)		(-3.517)**	(0.493)
Population growth in year *t*			-0.483			-0.471
			(-1.691)†			(-1.653)†
Trade openness in year *t*			-0.002			-0.002
			(-0.321)			(-0.255)
Political stability indicator			1.159			1.142
			(2.368)*			(2.248)*
Control of corruption indicator			2.471			2.492
			(3.662)**			(3.593)**
Dummy for developing countries			2.639 (2.214)*			2.641 (2.215)*
Dummy for moderate water scarcity	-1.062 (-1.029)	-0.737 (-0.795)	-1.653 (-2.958)**	-1.065 (-1.028)	-1.416 (-1.754)†	-1.674 (-2.980)**
Dummy for extreme water scarcity				-0.583 (-0.516)	-3.339 (-4.451)**	-0.295 (-0.233)
Inverted-U relationship	**Yes**	**Yes**	**Yes**	**Yes**	**Yes**	**Yes**
(Estimate of ρ^*)	(2.885)	(3.009)	(3.798)	(3.091)	(3.650)	(3.851)
Elasticity of ρ	**0.290**	**0.271**	**0.346**	**0.349**	**0.566**	**0.375**
(Sample mean of ρ)	(0.227)	(0.229)	(0.248)	(0.227)	(0.229)	(0.248)
(Sample mean of $g_{t,t+5}$)	(1.155)	(1.294)	(1.298)	(1.155)	(1.294)	(1.298)
Number of observations (N)	$N = 143$	$N = 132$	$N = 120$	$N = 143$	$N = 132$	$N = 120$
Wald statistic	91.960**	89.967**	57.288**	89.590**	84.960**	59.261**
Breusch-Pagan LM statistic	2.909	3.004	33.657**	2.808	2.886	34.605**

Notes: [a] Maximum likelihood estimation after correcting the variance-covariance matrix for multiplicative heteroskedasticity. *t*-statistics are in parentheses.

[b] Ordinary least squares employing standard errors based on White's heteroskedasticity-consistent variance-covariance matrix.

**Significant at 1% level. *Significant at 5% level. †Significant at 10% level.

Notes

[1] However, some water resource experts, while not minimizing the potential threat of water scarcity, are less sanguine about the accuracy of future projections of global and regional water shortages (Gleick 2000). Because future technical, efficiency and institutional improvements are so difficult to predict, current projections of future water use vary widely. For example, two diverging studies projecting the increase in world water demand over 1995 to 2025 suggest that the increase could be as little as 13% or as much as 37% (Cosgrove and Rijsberman 2000).

[2] The increasing role of the private sector in the provision of water services in some economies is discussed further in the conclusion, particularly with regard to improving the efficiency of water use. However, the use of institutions such as water markets and privatized water utilities does not necessarily detract from the overall view of water as a congestible public good, nor does it affect significantly the assumption that it is a public authority that is ultimately responsible for providing this good, even though the authority may decide that the most efficient way of providing some services is to allow regulated private entities be the ultimate end-use supplier. See Dosi and Easter (2000) and Johnstone and Wood (2001) for further discussion. See also note 7, which discusses how the model of this paper could be compatible with either public or private provision of "delivered" water.

[3] Interestingly, the authors suggest that "water systems" are a good example of this type of congestion model of economic growth Specifically, Barro and Sala-I-Martin (1992, p. 650) state: "The congestion model applies readily to highways and other transportation facilities, water and sewer systems, courts, etc."

[4] In these studies, the definition of *absolute* or *physical water scarcity* is that, even with the highest feasible efficiency and productivity of water use, countries will not have sufficient water resources to meet their agricultural, domestic, industrial, and environmental needs in 2025. *Economic water scarcity* means that countries have sufficient water resources to meet their needs in 2025 but these countries face severe financial and capacity problems in increasing their additional water storage, conveyance and regulation systems.

[5] See Faurés *et al.* (2001) for the FAO AQUASTAT methodology. Surface water resources are usually computed by measuring or assessing total river flow occurring in a country on a yearly basis. Groundwater resources are expressed as a measure of aquifer recharge through infiltration. In arid areas, groundwater is estimated in terms of recharge from rainfall, whereas in humid areas aquifer recharge is associated with the base flow of connected river systems.

[6] The original development of the water stress or scarcity index is attributed to the Swedish hydrologist Malin Falkenmark. The Falkenmark index suggests that water stress for a country begins when there is less than 1,700 cubic meters of freshwater available per capita per year. When the index reaches 1,000 m^3/year per capita, then water stress is severe. For further discussion, see Falkenmark (1989) and Falkenmark and Rockström (1998).

Hydrologists also use the UN's "criticality ratio" of water withdrawals relative to the total freshwater renewable resources avaible to each country annually (Cosgrove and Rijsberman 2000; United Nations 1997). Vörösmarty *et al.* (1999) refer to the "cricitcality ratio" as "relative water demand" (RWD). An RWD value between 0.2 to 0.4 indicates medium to high stress, whereas a value greater than 0.4 reflect conditions of severe water limitation.

[7] As noted by Barro (1990), the government could be one of the producers in the economy with production function (1). Equally, the output, y_i, which results from production may itself be "delivered" water. Both factors may be particularly important with respect to domestic water use, where the producer supplying water directly to consumer households could be either a privately or publicly owned utility. However, regardless of who owns the water utility, this "producer" of "delivered" water to domestic households would have to compete with producers in the agricultural and industrial sectors for available water supplies in the entire economy. Such aggregate supplies of water therefore still have the characteristic of a public good subject to congestion, and thus equation (1) applies to all private and public production in the domestic, industrial and agricultural sectors of an economy that utilize water.

[8] A specific functional form for $z(\rho)$ corresponding to (2) might be $\alpha\rho^{\gamma}$, $\beta = \alpha\gamma$.

[9] The proof is available from the author upon request.

[10] If water scarcity is not binding, i.e. $\mu(t) = 0$, then condition (8) reduces to $f(z(\rho)) = (1 - z(\rho))f'(z(\rho))$. Efficient water use requires that the marginal benefit of an increase in the rate of water utilization, $f'(z(\rho))/f(z(\rho))$, must equal its marginal cost, $1/(1 - z(\rho))$. The benefit of increased water utilization in the economy is that it contributes to more aggregate per capita output. The cost is that the government must appropriate a larger proportion of aggregate output to provide water supplies to the economy. The above equation is therefore the social efficiency condition determining the optimal rate of water utilization, if the economy does not face any binding water scarcity constraint.

[11] It follows that, for the water-constrained economy, condition (8) is now

$\lambda[(1-\alpha)Akf'(\alpha)\beta - Akf(\alpha)\beta] = \mu[Akf(\alpha)\beta + \alpha Akf'(\alpha)\beta]$ or $\mu = \lambda\left[\frac{f'(\alpha)}{f(\alpha) + \alpha f'(\alpha)} - 1\right] > 0$. The latter condition (17) determines the optimal use of water in the water-constrained economy. From the complementary slackness condition, $\mu > 0$, and as $\lambda > 0$, which means $\frac{f'(\alpha)}{f(\alpha) + \alpha f'(\alpha)} > 1$, i.e. in the water-constrained economy the marginal benefit of an extra unit of water in terms of its marginal productivity contribution always exceeds the social cost of providing water. A binding water scarcity constraint implies that it is socially optimal for the government to choose the maximum rate of appropriating economic output in order to supply freshwater, $\alpha y = r = w$, as the benefits of water use will always outweigh the costs of appropriation.

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[12] For the proof, see the previous note.

[13] The proof is available from the author upon request.

[14] The original "fixed" variables chosen by Sala-I-Martin (1999) included life expectancy in the initial year rather than the secondary-school enrollment rate. The author justifies the use of the latter two variables because "both are reasonable and widely used measures of the initial stock of human capital" (Sala-I-Martin 1999, p. 180). However, Temple (1999, p. 135) has argued that to include primary-school enrollment rate without also including the secondary-school enrollment rate, or vice versa, "tends to exaggerate the variation in human capital across countries." Following this approach, we therefore include the secondary-school enrollment rate in the initial year as one of our three "fixed" variables. We exclude life expectancy because there were a significant number of missing observations in this data series for the countries in our sample.

[15] The World Bank's governance data set covers 178 countries and therefore is the best match for the 163 countries of our sample of all the institutional data series currently available. The indicators in this data set are based on data referring to 1997-8 and are measured in units ranging from about -2.5 to 2.5, with higher values corresponding to better governance outcomes (e.g. greater political stability or control of corruption). The FAO classification of developing countries excludes the advanced economies of the Organization for Economic Cooperation and Development, the former Soviet republics and Eastern European countries in transition, South Africa and Israel.

[16] For example, the convergence hypothesis of neoclassical growth theory suggests that growth should be negatively correlated with the log of initial per capita income, a finding which is confirmed in much of the empirical growth literature. The latter literature also suggests that growth rates in poorer (i.e. developing countries) should be higher than in rich countries. In addition, growth should decline with increased population growth but should increase with improved "institutional quality", such as the control of corruption and political stability, and with greater school enrollment rates. For further discussion, see Agénor (2000); Barro and Sala-I-Martin (1995); Keefer and Knack (1997); Sala-I-Martin (1999) and Temple (1999).

[17] The countries are Bahrain, Kuwait, Libya, Malta, Qatar, Saudi Arabia and the United Arab Emirates. Note that Kuwait, Libya, Qatar and the United Arab Emirates do not appear in the regression sample as observations of five-year average annual growth rates could not be obtained for these countries over the specified time periods.

[18] In fact the sample for the regression is even smaller as four of the countries, Jordan, Kuwait, Libya, Qatar and the United Arab Emirates, do not have observations for five-year annual growth rates.

[19] The year 2000 level of population was preferred to population in 2025 because we are estimating the effects of potential water scarcity on five-year average annual growth rates during the 1980s and 90s for most countries.

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[20] Thus, as noted by Gleick (2000, p. 26), "the theoretical water availability rarely represents the actual water available to any particular person, which depends on economic factors, legal water rights, technical ability to capture, store, and move water from place to place, political agreements with neighboring countries, and so on....On paper, the Sudan has a vast amount of water available on average, but it is compelled by a treaty signed with Egypt to pass on much of the water it receives in the Nile from upstream nations. In recent years, internal turmoil and civil war have prevented the Sudan from using even its legal share from the Nile treaty."

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