THE ECONOMIC RECORD, VOL. 80, NO. 248, MARCH, 2004, 1–16

Water and Economic Growth*

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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 utilisation on economic growth is depicted through a growth model that includes this congestible nonexcludable 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 utilisation. Cross-country estimations confirm this relationship and suggest that for most economies current rates of fresh water utilisation are not yet constraining growth. However, for a handful of countries, moderate or extreme water scarcity may adversely affect 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. These results suggest caution over the claims of some hydrological-based studies of a widespread global 'water crisis'.

I Introduction

Recent hydrological projections of the world's fresh water resources have pointed to an emerging global threat, the dwindling supply of fresh water 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 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.

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* Invited address, Australian Conference Of Economists, Glenelg, South Australia, Australia, 1–3 October 2002. I am grateful to Richard Damania, Keith Hancock, Patrik Hultberg, Chuck Mason and two anonymous referees for helpful comments, to Lee Bailiff for research assistance and to Margie Reis for assistance in manuscript preparation.

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[1] However, some water resource experts, while not minimising 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 1995–2025 suggest that the increase could be as little as 13 per cent or as much as 37 per cent (Cosgrove & Rijsberman 2000).

Modelling 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 utilised by a country as a government-provided nonexcludable good subject to congestion.[2] Following the approach of Barro (1990) and Barro and Sala-I-Martin (1992), modelling the influence of water utilisation 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 nonexcludable 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 fresh water 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 utilisation 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 economic growth and the rate of water utilisation. The socially efficient rate of water utilisation 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 per capita output and consumption in 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 utilisation 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 hypothesised inverted-U relationship between economic growth and the rate of water utilisation across countries. Estimations of this relationship also suggest that current rates of fresh water utilisation in the vast majority of countries are not yet constraining economic growth. To the contrary, there is probably scope for many countries to increase fresh water 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 hydrologically-based studies that by 2025 at least 17 countries are likely to face 'absolute' water scarcity, and an additional 24 countries may

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[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 privatised water utilities does not necessarily detract from the overall view of water as a congestible nonexcludable 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 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.' Futagami *et al.* (1993) extend the model by Barro (1990) to include both public and private capital, which allows the additional advantage of being able to analyse the transitional dynamics of an economy to its steady-state. As public infrastructure is an important input in the supply of water provided to producers, depicting water supply as a nonexcludable, congestible good produced through public capital accumulation would be an interesting theoretical extension of the current paper. For example, denoting g as public infrastructure per person and r as fresh water utilisation per capita, one could depict $r = r(k_g)$, $r' > 0$, $r'' < 0$, and equation 2 in the model of this paper, below, would be modified to $\dot{k}_g = z(\rho)$, with the function z having the same properties defined in equation 2.

face 'economic' water scarcity (Seckler *et al.* 1999; Cosgrove & Rijsberman 2000).[4]

The paper is organised 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 utilisation and that water scarcity may affect this relationship adversely. The conclusion summarises the main findings and results of the paper, and discusses recent institutional innovations that may improve the efficiency of water use in economies.

II A Model of Water Use and Economic Growth

The most common measure of aggregate fresh water 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 (Gleick 1998, 2000; Faurés *et al.* 2000).[5] In the following analysis, we will use this flow indicator as our measure of the total renewable fresh water 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 fresh water 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 fresh water withdrawals amounted to 3 800 km^3, of which 2 100 km^3 was consumed.

These standard hydrological definitions of water withdrawal, consumption and availability imply very limited temporal and geographical scales. Ecological damage and losses of hydrological functions may take several years to affect the availability of fresh water in a region, and in poor economies there is the additional problem that the effective supplies available to producers and households may be less than actual supplies due to lack of access to safe water and the time spent collecting water (Sullivan 2002). Assessing the fresh water supplies of a country can sometimes be arbitrary, as major rivers, lakes and other water bodies often transcend political boundaries (Gleick 2000). Thus, as argued by Sullivan (2002, pp. 1205–6), a more comprehensive water use index relative to supply should take into account 'physical water availability, water quality and ecological water demand', and include as well as 'social and economic measures of poverty', thereby linking 'macro-level hydrological date reflecting regional or catchment-level water availability and microlevel data on household water stress.' However, to date, such a comprehensive water use index has yet to be developed for a cross-section of regions or countries.

In this study, we will use average annual water withdrawals (km^3/year) as our measure of fresh water utilisation. 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 metres per person per year) or in terms of relative water demand (the ratio of water withdrawals to total fresh water resources per year).[6] When the latter measure is employed, hydrologists typically

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[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] Faurés *et al.* (2000) for the FAO AQUASTAT methodology. Surface water resources are usually computed by measuring 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 metres of fresh water available per capita per year. When the index reaches 1 000 m^3/year per capita water stress is considered severe. For further discussion, see Falkenmark (1989) and Falkenmark and Rockström (1998). Hydrologists also use the UN's 'criticality ratio' of water

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 & 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 utilisation relative to fresh water availability*, to be the critical indicator.

Let w be the annual per capita renewable fresh water resources of a country (in cubic metres per person per year), and let r be total per capita fresh water utilisation by that country (in cubic metres 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 utilised by a country, for domestic, agricultural and industrial purposes, has the characteristics of a government-provided nonexcludable good subject to congestion. That is, modelling 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 government-provided good as a productive input for private producers.

The contribution of water utilisation or withdrawal, r, to the per capita output of the ith producer, y_i, can therefore be represented as

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

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 utilisation, which is supplied through public services. However, because of congestion, the flow of water available to the ith 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 utilisation, r, has to increase relative to y in order to expand the water available to the ith producer. In contrast, an increase in per capita output relative to total water utilisation in the economy lowers the water available to each producer, and therefore reduces y_i in equation 1.

Note, however, that the specification of equation 1 captures only the nonexcludable aspect of immediate water utilisation among producers. What is missing from equation 1 is any consideration of how aggregate water utilisation in the economy may generate feedback effects over time in terms of reduced ecological services and thus aggregate output. As discussed previously, in some regions the cumulative ecological damages and losses of hydrological functions that arise from aggregate water utilisation may affect the availability of fresh water, although this feedback effect may take years or even decades to manifest itself in terms of impacting economic output (Sullivan 2002).

Not only may the aggregate water supplies in an economy have the characteristic of a nonexcludable good subject to congestion, but also the provision of these supplies may be affected by their physical availability, 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 modelling the supply of general public goods, Barro (1990) has argued that one can think of government as 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 utilised by the economy, r, one can also envision the government purchasing or

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withdrawals relative to the total fresh water renewable resources available to each country annually (United Nations 1997; Cosgrove & Rijsberman 2000). Vörösmarty *et al.* (2000) refer to the 'criticality ratio' as 'relative water demand' (RWD). An RWD value between 0.2 and 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 represented by equation 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 utilise water.

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 fresh water utilisation in the economy, r, rises relative to the available annual per capita renewable fresh water resources, w, one would also expect that more aggregate output must be allocated for water supply. As water becomes increasingly scarce, i.e. water utilisation rises relative to available fresh water resources, the government must exploit less accessible sources of fresh water. 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 utilisation relative to total fresh water availability, it therefore follows that

$$\begin{aligned} &r = z(\rho)y, \quad z' > 0, \quad z'' > 0, \quad z(0) = 0, \\ &z'(0) = 0, \quad z(1) = \alpha, \quad z'(1) = \beta < \infty, \end{aligned} \tag{2}$$

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 utilisation by the economy relative to its fresh water resources, ρ. In addition, as aggregate output, y, rises in the economy, so does water utilisation, r. Finally, as water becomes increasingly scarce, i.e. $\rho \rightarrow 1$, 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 utilisation in an economy by limiting the total amount of water available for withdrawal. That is, even if all fresh water resources are used (i.e. $\rho = 1$), water withdrawals are finite. Thus total per capita fresh water availability imposes the following constraint on the economy

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

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

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

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

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. Maximisation of W with respect to choice of c and ρ, subject to equations 1 to 4, yields the following Lagrangian expression, L, comprising the current-value Hamiltonian for the problem specified by equation 5 subject to equation 4, plus the constraint on the control variable r given by equation 3

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

The resulting first-order conditions are

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

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

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

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

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 utilisation of the economy, including the complementary slackness condition imposed by the water scarcity constraint. The Lagrangian multiplier μ can be interpreted as the scarcity value of fresh water supplies to the economy. Equation 9 indicates the change over time in the marginal imputed value of the capital stock of the economy. Finally, equation 10 is the transversality condition for this infinite time horizon problem.

Differentiating equation 7 with respect to time and substituting into equation 9 yields

$$\begin{aligned} g &= \frac{\dot{c}}{c} \\ &= \frac{1}{\theta}\Bigg[(1 - z(\rho))Af(z(\rho)) - (\omega + n + \delta) \\ &\quad - \mu\frac{z(\rho)Af(z(\rho))}{c^{-\theta}}\Bigg]. \end{aligned} \tag{11}$$

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

The above equation indicates that growth in per capita consumption is negatively affected by the government's appropriation of output to supply water, $z(\rho)$, 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 (equation 3) is binding or not. We begin with the interior solution in which the economy is not constrained by per capita fresh water availability.

(i) Case 1. Water Scarcity is not Binding in the Economy

If the water scarcity constraint (equation 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

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

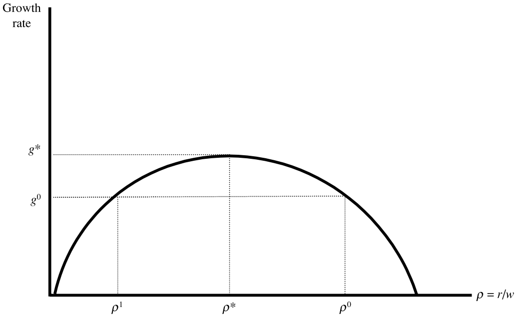
Although water scarcity no longer affects the growth in per capita consumption, g is still influenced by water utilisation in the economy. Growth is negatively affected by the government's appropriation of output to supply water, $z(\rho)$, and positively influenced by the contribution of water use to 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 equation 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 equation 12.

It is also straightforward to demonstrate that the socially efficient rate of water utilisation, ρ^*, maximises growth in the economy. Differentiating equation 12 with respect to ρ we get

$$\frac{\partial g}{\partial \rho} \gtreqless 0 \quad \text{if} \quad f(z(\rho)) \lesseqgtr (1 - z(\rho))f'(z(\rho)). \tag{13}$$

Thus, the socially efficient rate of water utilisation that satisfies equation 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 equation 12 with respect to the rate of water utilisation 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 utilisation is concave.

FIGURE 1
Growth and the Rate of Water Utilization for the Interior Solution



However, current policies for supplying water in most countries, even those that do not face binding water scarcity constraints, are not socially efficient (Dosi & Easter 2000). For example it is possible that water management in some countries may lead to a rate of water utilisation 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 from the provision of water are not 'contributing' a sufficient share of the social costs of providing this non-excludable good.

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

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[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 utilisation, $f'(z(\rho))/f(z(\rho))$, must equal its marginal cost, $1/(1 - z(\rho))$. The benefit of increased water utilisation 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 utilisation, if the economy does not face any binding water scarcity constraint.

(ii) Case 2. The Water-Constrained Economy

We now turn to the case where the water scarcity constraint equation 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.[11]

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, α, 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 fresh water.[12]

For the water-constrained economy, condition 8 becomes $\mu = \lambda\left[\frac{f'(\alpha)}{f(\alpha) + \alpha f'(\alpha)} - 1\right] > 0$.[13] Using the latter expression, equation 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 equation 15.[14] In the initial period, the government chooses the maximum rate of appropriating economic output in order to supply fresh water, $\alpha y = r = w$, 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 equation 15.

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

$$g_S \gtreqless 0 \quad \text{if} \quad Af(\alpha) - (\omega + n + \delta) \gtreqless \alpha A f(\alpha)\frac{f'(\alpha)}{f(\alpha) + \alpha f'(\alpha)}. \tag{16}$$

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.

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[11] If both α and w are constant then it follows from this constraint that y must also be constant; i.e. there is no growth in per capita income in the water-constrained economy. To rule out this outcome and to make this case interesting, we assume that, by appropriating output at its maximum rate, the government is able to increase fresh water availability, although not sufficiently to overcome the binding constraint, i.e. $\alpha y = w = r$. Essentially, there are two ways that a government might increase w in a water-constrained economy. First, it might invest in improved wastewater treatment to increase the rate of recovery and return of water withdrawals to the original fresh water sources. Second, it might invest in desalinisation plants to augment fresh water sources with converted sea and brackish water. Both approaches are common, albeit expensive, options currently being explored by water-constrained economies in the world (Gleick 2000).

[12] 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 fresh water, $\alpha y = r = w$, as the benefits of water use will always outweigh the costs of appropriation.

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

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

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 fresh water 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.

III Cross-Country Empirical Analysis of Water and Growth

The above theoretical analysis of the relationship between growth and water utilisation suggests the possibility of a concave, or 'inverted-U', relationship (see equation 13 and Figure 1). That is, as the rate of water utilisation, ρ, in an economy increases, economic growth, g, first increases, then stabilises 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 utilisation for a broad cross-section of countries? The rest of this section summarises one approach to testing this hypothesis through a cross-country analysis.

The key variable in this analysis is of course the rate of water utilisation, ρ. A recent assessment of the world's fresh water supplies provides estimates of the annual renewable water resources and the total amount of fresh water withdrawal for a single year of estimate for 163 countries (Gleick 1998, 2000). The ratio of fresh water withdrawals, r, relative to supplies, w, can therefore serve as our cross-country measure of $\rho = r/w$.

Ideally, one would want to test any relationship between growth and r through a pooled cross-sectional and time series (i.e. panel) analysis. However, the World's Water database reports only a single-year estimate of fresh water 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 per capita growth in GDP and ρ through a cross-sectional as opposed to a panel analysis. Thus, the following empirical analysis must be considered only a preliminary test of the theoretical model, as the results obtained may arise from the use of our limited cross-country data set. A more robust test of the theory must wait until a better (i.e. pooled cross-sectional and time series) data set becomes available.

In empirically examining the hypothesised 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 5- or 10-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 5-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 1994–99 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.

(i) Model Description and Data

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 in per capita GDP and the rate of water utilisation across countries:

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

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 & 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 hypothesised U-shaped relationship between growth and the rate of water utilisation 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:

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

Following Sala-I-Martin (1999) and Temple (1999), we choose the 'fixed' variables, $\boldsymbol{x}$, to be the initial level of income per capita in year t, the primary-school enrolment rate in year t and the secondary-school enrolment rate in year t.[15]

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 & Warner 1995; Sachs & Warner 1997; Sala-I-Martin 1999; Temple 1999). This suggests that, extending our growth model further to include these additional explanatory variables, $\boldsymbol{y}$, should not affect the hypothesised U-shaped relationship between growth and the rate of water utilisation, if that relationship is robust. Our full growth model for empirical estimation is:

$$g_{t,t+5} = b_0 + b_1\rho_t + b_2\rho_t^2 + \boldsymbol{b}_x\boldsymbol{x} + \boldsymbol{b}_y\boldsymbol{y} + \mu, \qquad (19)$$

where $\boldsymbol{y}$ 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 5-year average cross-country growth rates, g, and the various variables comprising $\boldsymbol{x}$ and $\boldsymbol{y}$ 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, 1999b), and the dummy variable for developing countries, which uses the UN Food and Agricultural Organisation classification of countries.[16]

(ii) Estimation Results

Table 1 summarises the growth regression results for equations 17, 18 and 19.[17] As the Wald statistic

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[15] The original 'fixed' variables chosen by Sala-I-Martin (1999) included life expectancy in the initial year rather than the secondary-school enrolment 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 the primary-school enrolment rate without also including the secondary-school enrolment rate, or vice versa, 'tends to exaggerate the variation in human capital across countries'. Following this approach, we therefore include the secondary-school enrolment 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.

[16] 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 1997–98 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 Organisation for Economic Cooperation and Development, the former Soviet republics and Eastern European countries in transition, South Africa and Israel.

[17] As an alternative to equation 17, a non-linear estimation of the relationship between 5-year average cross-country growth rates, g, and the rate of water utilisation, ρ, was

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†	Basic Growth Model†	Full Growth Model‡
Constant	0.818 (2.432)**	−1.275 (−0.685)	9.569 (2.534)**
ρ	1.614 (5.117)*	1.647 (5.828)*	1.947 (2.515)**
ρ^2	−0.279 (−6.815)*	−0.273 (−7.024)*	−0.257 (−2.577)*
Log per Capita Income in Year *t*		−0.042 (−0.146)	−1.538 (−3.379)*
Primary School Enrolment in Year *t*		0.029 (2.138)**	0.016 (1.096)
Secondary School Enrolment in Year *t*		−0.005 (−0.383)	0.009 (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*)	$N = 143$	$N = 132$	$N = 120$
Likelihood Ratio Test	10.617*	18.529*	38.520*
Wald Statistic	99.500*	88.110*	104.799*
Breusch-Pagan LM statistic	1.743	2.936	32.831*

t-statistics are in parentheses.
† Maximum likelihood estimation after correcting the variance–covariance matrix for multiplicative heteroskedasticity.
‡ 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.

and Breusch–Pagan Lagrange multiplier tests imply, all models required correction either for multiplicative heteroskedasticity using maximum likelihood estimation or for generalised heteroskedasticity using White's consistent estimator.[18] The likelihood ratio test statistic is also significant for all regressions in Table 1, which suggests that the hypothesis that all regression coefficients should be restricted to zero can be rejected. An examination of the pairwise simple correlations of the independent variables of

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attempted. The alternative non-linear relationship was $g_{t,t+5} = e^{b_0+b_1\rho_t} + \mu$, which was estimated through both non-linear ordinary and weighted least squares. None of the coefficients in the latter regressions were significant. In addition, for both regressions the Wald test of the hypothesis that the coefficients are not significantly different from zero was not significant. Thus the hypothesis could not be rejected. Extending the two non-linear regressions to include ***x*** and ***y*** variables as alternatives to equations 18 and 19 produced similar results. As a second alternative to equations 17–19, a model was estimated that included a cubic term for the rate of water utilisation, ρ^3. However, the coefficient for this term is insignificant, and its inclusion causes the signs of the coefficients for ρ and ρ^2 to reverse, reduces the overall explanatory power of the regressions, and fails to produce a significant Wald test. Thus the alternative cubic version of equations 17–19 is also rejected.

[18] Heteroskedasticity was detected through both visual inspection of the residuals and from employing two statistics for testing the hypothesis of homoskedasticity, the Breusch-Pagan Lagrange Multiplier statistic and the Wald statistic (Greene 1997). The latter two statistics are reported in Table 1, and the significance of one or both of them confirms the presence of heteroskedasticity. Two recommended procedures for estimating a heteroskedastic regression model were subsequently employed and compared: ordinary least squares employing standard errors based on White's heteroskedasticity-consistent variance–covariance matrix, and maximum likelihood estimation after correcting the variance–covariance matrix for multiplicative heteroskedasticity. In the latter procedure, the starting values of the regression coefficients are estimated through ordinary least squares, but convergence after multiple iterations is achieved through generalised least squares (see Greene 1997). Several versions of the multiplicative heteroskedasticity model were estimated, by testing for a specific type of heteroskedasticity, $\mathrm{var}(\varepsilon_i) = \sigma^2 e^{\gamma' z}$, associated with a subset of the explanatory variables, **z**. Comparisons across regressions of the likelihood ratio test and the *t*-statistic tests on individual coefficients led to the selection of the preferred estimated heteroskedastic regression models reported in Table 1.

the regressions in Table 1 indicates that these variables are not highly correlated with one another.[19]

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. Overall, the three regression models suggest that the hypothesis of an inverted-U relationship between growth and the rate of water utilisation 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 utilisation 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 utilisation at or exceeding these levels.[20] The vast majority of countries display rates of water utilisation 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 hypothesised 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.[21]

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

In sum, the regression results reported in Table 1 provide strong support for the hypothesised inverted-U relationship between economic growth and the rate of water utilisation across countries. Our estimations of this relationship also suggest that current rates of fresh water utilisation in the vast majority of countries are not constraining economic growth. To the contrary, most countries may be able to increase growth by utilising more of their fresh water 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

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[19] Correlation between the rate of water utilisation and the other explanatory variables listed in Table 1 appears to be particularly low. For example, the pairwise correlation coefficients between ρ and ρ^2, respectively, and the other explanatory variables ranges from -0.121 to 0.165. Only four pairs of explanatory variables in Table 1 display correlation coefficients greater than 70 per cent: log per capita income and control of corruption (0.788), dummy for developing countries and secondary school enrolment (–0.778), log per capita income and secondary school enrolment (0.775) and political stability and control of corruption (0.739).

[20] 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 5-year average annual growth rates could not be obtained for these countries over the specified time periods. Fifteen other countries also do not appear in the regression sample as observations of 5-year average annual growth rates could not be obtained for these countries either. One additional country does not appear in the regression sample as an observation of its rate of water withdrawal could not be obtained. In sum, whereas the full sample contains 163 countries, due to missing observations the largest regression sample reported in Table 1 is 143 countries.

[21] Given the limitations of the data, and in particular that the data are allowing estimation of only the left-hand part of the hypothesised inverted-U relationship in Figure 1, as an alternative specification to equations 17, 18 and 19 a reciprocal model of the relationship between 5-year average cross-country growth rates, g, and the rate of water utilisation, ρ, was attempted. For example, the reciprocal model $g_{t,t+5} = b_0 + b_1(1/\rho) + \mu$, $b_0 > 0$, $b_1 < 0$ would estimate the left-hand part of Figure 1; i.e. the curve would asymptotically approach the upper limit b_0, which would now also serve as the estimate of ρ^*. The reciprocal model was also extended to include the additional $\boldsymbol{x}$ and $\boldsymbol{y}$ explanatory variables for the basic and full growth models equations 18 and 19, respectively. The procedures outlined in note 18 for detecting and correcting heteroskedasticity in the regressions were followed. Although in all the regressions of the reciprocal model the estimated coefficients of b_0 and b_1 displayed the predicted signs, only b_0 was statistically significant. The coefficient b_1 and the coefficients for any additional $\boldsymbol{x}$ and $\boldsymbol{y}$ explanatory variables were always statistically insignificant in all versions of the reciprocal model. In addition, for all regressions, the likelihood ratio test statistic was not significant, suggesting that the hypothesis that all regression coefficients be restricted to zero cannot be rejected for any version of the reciprocal model. The latter model can therefore be rejected as an alternative to the inverted-U estimations of Figure 1 depicted in Table 1.

its rate of water utilisation, 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 fresh water, 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 fresh water 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 10 out of the 163 countries in our sample display rates of water utilisation of $\rho > 1$. This is too small a subsample for conducting a separate regression.[22] Second, as noted above, our data set contains only a single-year estimate of the rate of water utilisation for each country. Some countries that have rates of water utilisation of $\rho > 1$ 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 & Rockström 1998). The water stress index is constructed by taking a past level of renewable fresh water 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 metres per year per person is expected to experience only intermittent and localised water shortages, the threshold of 1 000 cubic metres is considered to be a level below which a country is likely to experience widespread and chronic shortfalls. At less than 500 cubic metres 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 fresh water supply for each country divided by its population in year 2000.[23] Sixteen countries face conditions of extreme water scarcity (less than 500 cubic metres/person/year), whereas four countries experience moderate water scarcity (between 500 and 1 000 cubic metres/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 summarises 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 generalised heteroskedasticity using White's consistent estimator.[24] The likelihood ratio test statistic is also significant for all regressions, which suggests that the hypothesis that all regression coefficients should be restricted to zero can be rejected for the regressions in Table 2.

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).[25] The hypothesis of an inverted-U relationship between growth and the rate of water utilisation cannot be rejected, and the estimates of the turning point for ρ

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[22] 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 5-year annual growth rates.

[23] The year 2000 level of population was preferred to population in 2025 because we are estimating the effects of potential water scarcity on 5-year average annual growth rates during the 1980s and 1990s for most countries.

[24] The same procedure for detecting and correcting for heteroskedasticity in the regressions for Table 1 was also followed for the regressions reported in Table 2. See note 18 for further details.

[25] An examination of the simple pairwise correlations between moderate and extreme water scarcity dummies, respectively, and the other explanatory variables in Table 2 indicates low correlation. All correlation coefficients are less than 50 per cent, and most fall in the range of −0.123–0.191.

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 ($g_{t,t+5}$)

	Moderate Water Scarcity			Moderate and Extreme Water Scarcity		
Variables	Base Case Model†	Basic Growth Model†	Full Growth Model‡	Base Case Model†	Basic Growth Model†	Full Growth Model‡
Constant	0.848 (2.461)**	−1.264 (−0.683)	9.652 (2.553)**	0.826 (2.395)**	−3.508 (−2.118)**	9.567 (2.534)**
ρ	1.602 (5.048)*	1.652 (5.895)*	1.939 (2.509)**	1.917 (3.250)**	3.404 (9.750)*	2.100 (2.015)**
ρ^2	−0.278 (−6.766)*	−0.275 (−7.135)*	−0.255 (−2.565)*	−0.310 (−4.964)*	−0.466 (−11.192)*	−0.273 (−2.183)**
Log per Capita Income in Year *t*		−0.034 (−0.120)	−1.550 (−3.400)*		0.375 (1.450)	−1.542 (−3.342)*
Primary School Enrolment in Year *t*		0.031 (2.305)**	0.017 (1.125)		0.040 (3.069)*	0.017 (1.125)
Secondary School Enrolment in Year *t*		−0.009 (−0.656)	0.009 (0.535)		−0.040 (−3.517)*	0.008 (0.493)
Population Growth in Year *t*			−0.483 (−1.691)***			−0.471 (−1.653)***
Trade Openness in Year *t*			−0.002 (−0.321)			−0.002 (−0.255)
Political Stability Indicator			1.159 (2.368)**			1.142 (2.248)**
Control of Corruption Indicator			2.471 (3.662)*			2.492 (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 (Estimate of ρ*)	**Yes (2.885)**	**Yes (3.009)**	**Yes (3.798)**	**Yes (3.091)**	**Yes (3.650)**	**Yes (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*)	$N = 143$	$N = 132$	$N = 120$	$N = 143$	$N = 132$	$N = 120$
Likelihood Ratio Test	12.908*	19.031*	38.7942*	12.778*	23.599*	38.189*
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*

t-statistics are in parentheses.

† Maximum likelihood estimation after correcting the variance-covariance matrix for multiplicative heteroskedasticity.

‡ 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.

and its elasticity are similar.[26] For the full growth model that includes the moderate water scarcity dummy, a 10 per cent increase in the rate of water utilisation again raises the average growth rate in the sample of countries from 1.30 per cent to 1.33 per cent. For the full growth model that includes both the moderate and water scarcity dummies, a 10 per cent increase in ρ will raise growth only slightly more, to 1.34 per cent.

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.

IV 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 utilisation on an economy in a growth model that includes this congestible nonexcludable 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 utilisation (see Figure 1). Moreover, the socially efficient rate of water utilisation 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 utilisation is likely to be more complex. Although it is always optimal for the government to appropriate output at the maximum rate, α, to supply fresh water, 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 fresh water resources, w, available to appropriate.

The empirical analysis of this paper provides strong support for the hypothesised inverted-U relationship between economic growth and the rate of water utilisation across countries. Our estimations of this relationship also suggest that current rates of fresh water utilisation in the vast majority of countries are not yet constraining economic growth. However, countries that are 'water stressed', i.e. have limited fresh water 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 that increased water utilisation may constrain growth in a handful of countries.

First, fresh water supplies and use rates vary considerably across the regions within a country. A country as a whole may appear to have sufficient fresh water 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 localised water scarcity. In particular, arid and semiarid regions of the world are the most vulnerable to future water stress (Vörösmarty *et al.* 2000). An important extension to the cross-country study of this paper would be to examine regional differences in growth within a country or countries, particularly where a large number of regions are experiencing moderate or severe water scarcity.

Second, a critical factor in assessing the actual amount of fresh water 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).[27]

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[26] The reciprocal model discussed in note 21 was also extended to include the moderate and extreme water scarcity dummies, as an alternative to the regressions reported in Table 2. However, the scarcity dummies were not significant in the reciprocal model, nor did their inclusion improve the poor overall performance of this model. The reciprocal model can therefore be rejected as an alternative to the estimations in Table 2.

[27] 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

Third, while water-scarcity constraints on overall economic growth may be less likely, fresh water 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 the world population increasing by 50 per cent over the next 30 years, water scarcity may become a key factor behind global food insecurity, reduced production growth and rising international cereal prices (United Nations 1997; Falkenmark *et al.* 1998; Seckler *et al.* 1999; Rosegrant & Cai 2001).

Fourth, this paper has focused fairly narrowly on the availability of fresh water supplies to provide economic uses of water. The wider ecological services provided by water have been ignored, and there is inevitably a trade-off between maintenance and protection of these services and the increasing allocation of water for use in the economy. As pointed out by Sullivan (2002), any resulting decline in the hydrological functions of ecosystems may in turn reduce future water availability.[28]

Finally, although in this paper it was analytically convenient to view water as a congestible, non-excludable 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 favour 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 utilisation in many countries (Briscoe 1996; Dosi & Easter 2000). Instead, providing an adequate supply of water to an economy and ensuring its efficient utilisation 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 & Tsur 1997). 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 (Dosi & Easter 2000; Johnstone & Wood 2001). It appears that, if the rate of water utilisation is to be socially efficient so as to maximise economic growth, then public as well as private sector involvement will be required as privatisation, 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.

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> place to place, political agreements with neighbouring 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.

[28] For example, Sullivan (2002, p. 1199) notes:

> . . . almost all natural ecosystems can perform valuable hydrological functions, such as water purification, flood control, habitat provision and groundwater recharge, and many of these can help to reduce both water stress and poverty.

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