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Operating Strategies for Hydropower Systems Using Unregulated Turbines

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Operating Strategies for Hydropower Systems Using Unregulated Turbines

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1. Introduction

For micro hydropower systems, say under 100 kW, there has been a growing interest in using turbines having no hydraulic controls. The financial savings from omitting control gear is substantial and further savings are possible if 'pumps', mass-produced in country, are used instead of individually designed turbines, often imported. There is now a considerable literature on the use and selection of pumps-as-turbines.

A common configuration of micro-hydro plant is for there to be very little water storage and therefore for the system gross head to be nearly constant. The speed of the turbine-generator set is held constant by electrical means. Thus the fixed geometry turbines run at constant flow. Unfortunately the river flow is never constant. When it exceeds the total turbine flow there is no problem, but when it is less than rated turbine flow there is a mismatch. The absence of storage (which is too costly) removes the possibility of filtering out river flow fluctuations.

There are three system/operation designs we might use in this context. The simplest way of operating (SO) is to employ a single turbine that runs only when river flow exceeds turbine rated flow. A second option is to employ several small turbines operating in parallel (PO): the number in use is varied to match the variation in river flow. A third option is to intermittently operate (IO) a single turbine fed from a small reservoir (*e.g.* holding only 15 minutes flow). It is the purpose of this paper to compare these three alternatives and to show that the third (IO) has apparent economic advantages over the others. All three alternatives can give higher economic returns in many semi-industrialised countries where, power for power, turbines cost over four times more than pumps.

In making economic comparisons there are a great many system variables and cost factors we might accommodate. To reduce the complexity of the analysis we will restrict ourselves to modelling hydro systems connected to a 'large' electrical grid. This allows us to reasonably assume that all the electrical energy produced will be purchased and that each unit will command the same (daily average) price. Even with this simplification, however, it has been necessary to develop a more flexible economic methodology than is normally used for evaluating hydropower. This methodology, described in section 5, is we hope of value in its own right independent of its specific application here.

The ensuing analysis is a simplified form of that developed in a PhD thesis from Warwick University, U.K. (Ref. 1).

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2. Option SO: Simple Operation of a Single Turbine

As observed above, at fixed head and speed an unregulated turbine will draw a constant rated flow, Q_R. Should this flow not be available ($Q_A < Q_R$), there are two operating alternatives. One is to shut down the turbine. The other is to let the water level in the penstock draw down until flow equilibrium is reached ($Q_A = Q_T$, $Q_T < Q_R$): reducing the effective gross head in this way will reduce the turbine flow. Although the second alternative is inefficient, since some head is being wasted and the turbine is being operated away from its best efficiency point (BEP), some power is better than none. Figure 1 shows the advantage of leaving the turbine running at low flow: typically an extra 10% energy can be obtained per year by doing so. In the subsequent analysis we assume alternative (ii) is followed. In practice, to avoid certain operational problems it is sometimes desirable to turn off the turbine flow when Q_A falls below say 60% of Q_R (which corresponds to very little power).

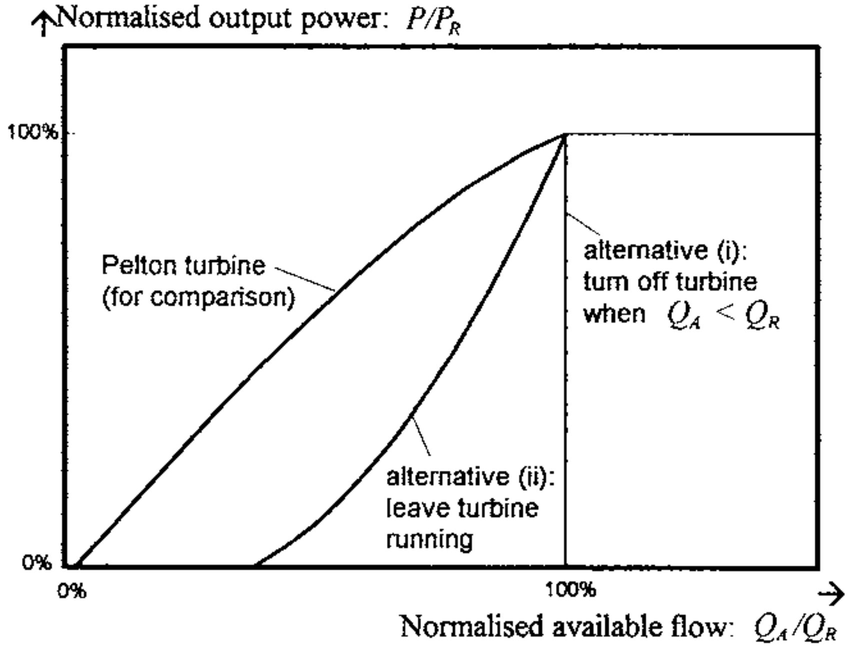

Figure 1: Advantages of operating a PAT with part-full penstock

In the design of this option the key variable is the size of the turbine and hence its rated flow Q_R. Increasing Q_R will increase the capital cost of the system. Up to some limit it will also increase the energy output. Using the economic model described later, by trial and error an optimum Q_R can be identified. It is such an optimised SO system we will later compare with optimised PO and IO systems.

3. Option PO: Several Turbines Operated in Parallel

If two or more PATs are operated in parallel, they can be switched on and off according to the available flow. Parallel operation (PO) of up to 7 machines has proven to be more cost-effective than a single conventional hydraulic turbine of comparable capacity, according to the literature (Ref. 2).

The machines can be different or identical to each other (for example, in a two-PAT scheme, the turbines can handle either ⅓ and ⅔ of the full flow, or one half each). The first option increases the energy generation, as it enables more combinations (in this case ⅓, ⅔ and ³⁄₃); the latter restricts the combinations (½ and ²⁄₂), but makes maintenance easier, as the same set of spares can be used in all machines.

Figure 2 shows the power output of a 5-turbine system. The solid line indicates some of the available flow is being spilled; the dashed line indicates where the penstock is not full; the numbers show how many machines are actively connected to the penstock. The shared penstock and equality of turbine sizes are common features of PO. The optimum number of machines is not however always 5 but depends, *inter alia*, on the variability of the river flow. In optimising a PO system we therefore need to find best values for two parameters: turbine number (n) and total rated flow Q_R.

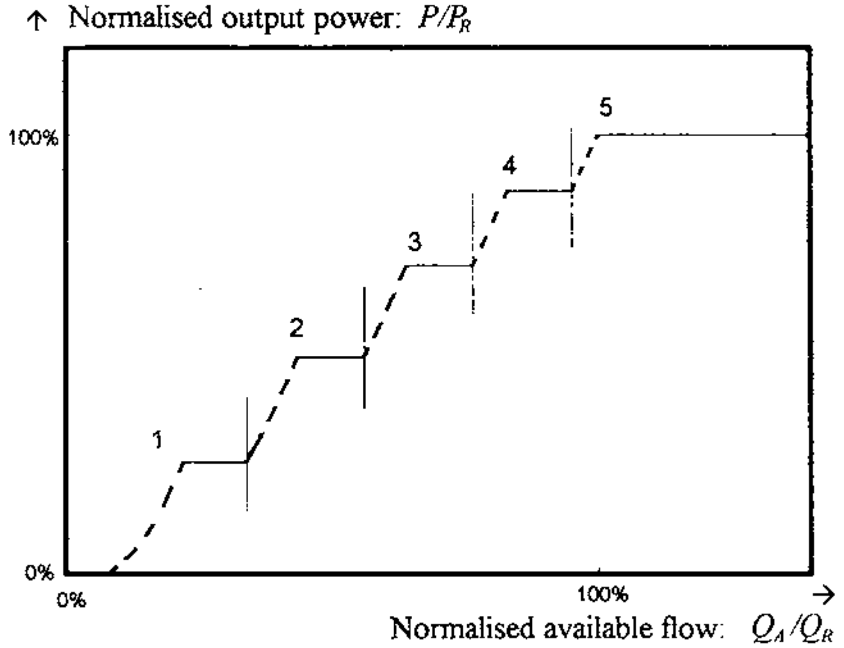

Figure 2. Parallel operation of five equal machines with common penstock.

4. Option IO: Intermittent Operation of One Turbine

When the river flow Q_A is less than the flow Q_R drawn by the turbine in operation, we might operate the turbine intermittently for a fraction Q_A/Q_R of the time. We will need a reservoir (in practice an enlarged forebay tank) whose level falls while the turbine is running and rises when the turbine is shut off. Figure 3 shows the cyclic operation. Although in theory the penstock could be opened and closed using a valve, in practice a quick-priming double siphon (see Fig. 4) would be used. Such siphons have no moving parts and can operate very swiftly.

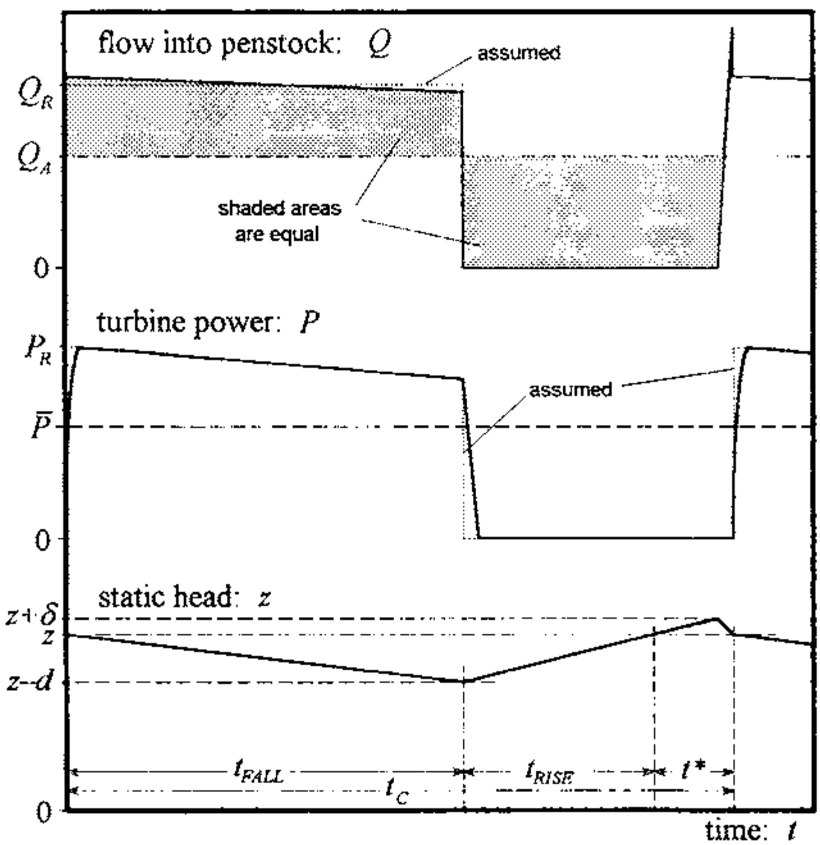

Figure 3. Schematic representation of the intermittent operation using a siphon (with d, δ, *etc.* exaggerated).
(t^* is the time to surcharge the reservoir with the water needed to refill the penstock.)

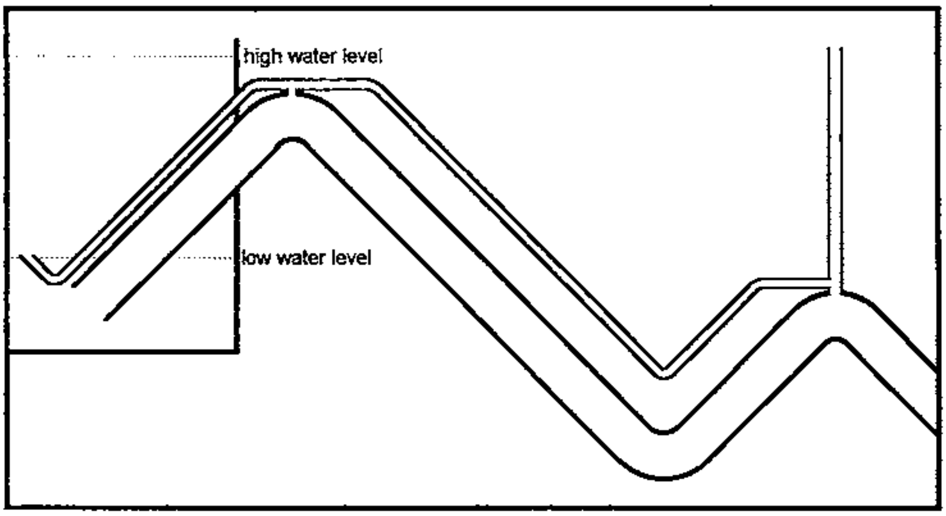

Figure 4. Schematic layout of a double-siphon, developed from a design described in Ref. 3. Performance and design procedure analysed in Ref. 1.

Technically therefore intermittent operation requires us to design an appropriate siphon and a penstock that will tolerate the sudden and frequent changes in flow. Using economic models we need to optimise three variables, namely the turbine size (Q_R), the drawdown (d) of the forebay tank and its effective surface area (A).

There are three regimes under which the system can operate. Where Q_A is greater than Q_R (regime ①) the turbine will run continuously at full power P_R and the tank will be both full and overflowing. Where Q_A is much less than Q_R (regime ②) the siphon will operate cyclically, the power output will be intermittent and the water level in the tank will fluctuate between height $z+\delta$ (rated gross head plus the small surcharge height δ) and height $z-d$ (see Fig. 3). If however Q_A is only slightly less than Q_R, we may observe regime ③ in which the turbine runs continuously but at a reduced head and flow: the water level will be steady somewhere between heights z and $z-d$.

This third regime is unfortunate as it may give less output power than when the flow is slightly lower (regime ②). Fortunately, with typical small values for drawdown ($d < .05{\cdot}z$), the system spends very little time operating in regime ③ and to simplify the discussion we can neglect it. Figure 5 shows the power output of a typical system.

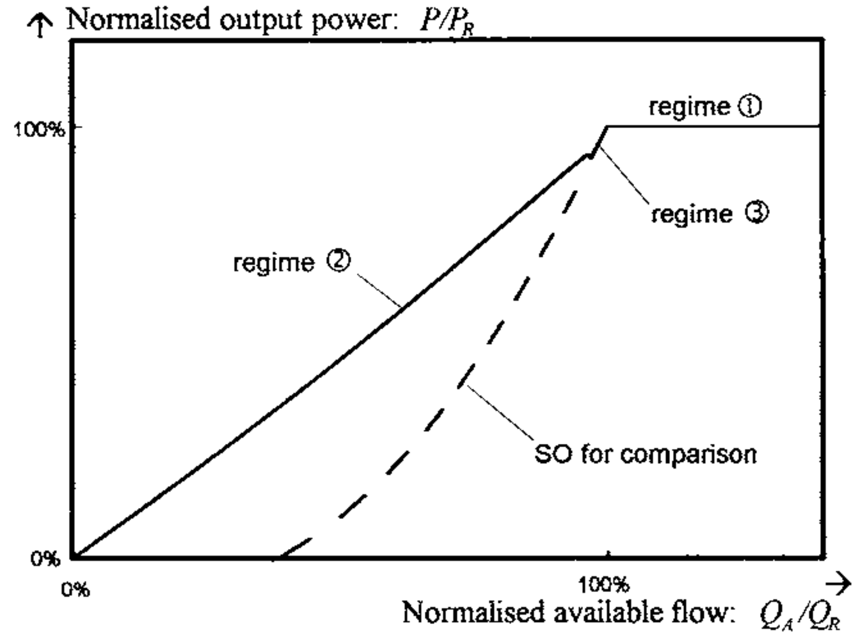

Figure 5. Power *versus* flow for intermittent operation.

The drawdown height (d) and the corresponding drawdown volume ($A{\cdot}d$) affect the power output during regime ②. A full analysis is given in Ref. 1 and is complex. Fortunately the optimum value of d is such a small fraction of gross head that we can use an approximate analysis in which

* Q is assumed to remain constant at Q_R as the tank level draws down
* the mean gross head during turbine operation is not z but $z-d/2 = z(1-d/2z)$
* the ideal cycle time $t_C = t_{FALL}+t_{RISE}$ is extended an extra period t^* during which the tank overfills by volume V^* which is effectively lost each cycle. As an approximation we can equate V^* to the penstock volume.

The effect of the last assumption is that the cycle time t_C is increased by factor X and the mean power correspondingly decreased.

$$X = \frac{t_{FALL} + t_{RISE} + t^*}{t_{FALL} + t_{RISE}} = \frac{\frac{dA}{Q_R - Q_A} + \frac{dA}{Q_R} + \frac{V^*}{Q_R}}{\frac{dA}{Q_R - Q_A} + \frac{dA}{Q_R}}$$

$$X = 1 + \frac{V^*}{dA}\left(1 - \frac{Q_A}{Q_R}\right) \qquad [1]$$

So mean power is

$$\overline{P} = \frac{P_R\left(1 - \frac{d}{2z}\right)}{1 + \frac{V^*}{dA}\left(1 - \frac{Q_A}{Q_R}\right)} = P_R \frac{1 - \alpha d}{1 + \frac{\beta}{d}} \qquad [2]$$

We may decide to choose d to simply maximise power regardless of its influence on cost. If so, differentiating the function of d in Eq. [2] and setting to zero gives

$$d_{\text{MAX.POW}} = \sqrt{\beta^2 + \frac{\beta}{\alpha}} - \beta$$

$$\frac{d_{\text{MAX.POW}}}{z} = 2\sqrt{\alpha^2\beta^2 + \alpha\beta} - 2\alpha\beta$$

then, since $\alpha \cdot \beta \ll 1$ typically,

$$\frac{d_{\text{MAX.POW}}}{z} \approx 2\sqrt{\alpha\beta}$$

$$d_{\text{MAX.POW}} \approx \sqrt{\frac{2zV^*}{A}\left(1 - \frac{Q_A}{Q_R}\right)} \qquad [3]$$

This power-maximising drawdown varies with flow from 0 at ($Q_A = Q_R$) to $\sqrt{\frac{2zV^*}{A}}$ at no flow. Although a variable drawdown siphon is feasible, it will normally suffice to use a fixed drawdown for all flows, choosing a flow of *e.g.* $Q_A = 0.8 \cdot Q_R$ to get close to the flow-averaged optimum. Alternatively we can employ a 'hill-climbing' search, using a spreadsheet version of the full economic model, to optimise all three variables d, A and Q_R.

5. Economic Modelling

There are many economic measures we might use for comparing alternative hydro system designs for a particular site. They all combine the initial cost, any running costs and the income earned through the life of the system into a single measure. The most usual measures are internal rate of return (IRR), benefit-cost ratio (BCR), payback time (PB) and net present value (NPV). IRR, BCR and PB reflect the financial return per unit of money invested, whereas NPV reflects the return "per site"; a system sized to maximise the latter will be larger than one sized to maximise the former three. As hydropower systems are capital intensive and microhydro schemes are particularly vulnerable to capital shortage,. we choose the return-per-unit-of-money-invested approach, *i.e.* the former three measures. Moreover, as we are dealing with systems whose expected incomes per year remain constant over their lives, and whose lives are long, it can be shown that the economic ranking of alternative designs will be the same whichever of the three measures (IRR, BCR or PB) we choose. As the calculation of BCR and PV (and NPV) requires the prior choice of a discount rate, we prefer the IRR as our measure and the ratio of their respective IRRs as our criterion for comparing two alternatives. IRR is the solution of:

$$\frac{\mathrm{IRR}(1+\mathrm{IRR})^N}{(1+\mathrm{IRR})^N - 1} = \frac{\mathrm{NAI}}{\mathrm{CAP}} \qquad [4]$$

where N is project life, NAI is annual income net of running costs and CAP is capital invested. As we are normally interested in IRR values greater than 15% and system lives of over 25 years, we can approximate Eq. [4] within 3% error to:

$$\mathrm{IRR} \approx \frac{\mathrm{NAI}}{\mathrm{CAP}} \qquad [5]$$

The net annual income is equal to gross annual income minus the annual operating and maintenance costs. These O&M costs are usually a function of capital costs. However, for the sake of simplicity, we will assume that they are a fixed multiple of the gross annual income. The error incurred will be negligible since O&M costs in microhydro are minor. This leaves the task of estimating gross annual income (GAI) which is affected by river flow. The flow can be described by a hydrological probability function

$$F_{Q_A} = \mathrm{Prob}(Q < Q_A) \qquad [6]$$

The relationship between output power and flow varies from design to design and is expressed by the technical function of each

$$P = \mathrm{T}(Q_A) \qquad [7]$$

(See Figs. 1, 2 and 5 as examples.) At a given output power, an economic function determines the rate of earning money

$$R = \mathrm{E}(P) = \text{typically } K_E P^{\Gamma} \qquad [8]$$

The parameter Γ can be taken as 1 for grid connected systems so K_E becomes the economic value of 1 Joule and gross annual income is

$$\mathrm{GAI} = \int_0^{\infty} K_E' \,\mathrm{T}(Q_A)\, dF_{Q_A} \qquad [9]$$

(Where $K'_E = K_E \times 3.16 \times 10^7$ s.) The following hydrological probability function (proposed in Ref. 1) fits very well the typical flow-duration curves in the range of interest for micro-hydro (*i.e.* the range of flows smaller than the average annual flow):

$$F_{Q_A} = e^{\lambda Q_A^{-\mu}} \qquad [10]$$

The numerical integration of Eq. [9] using a distribution such as [10] gives us income. We now need a flexible expression for capital cost.

Let
$$\mathrm{CAP} = C_T + C_P + C_S + C_R \qquad [11]$$

where the cost components represent respectively turbomachines, penstock, storage and the rest of the system.

Noting the economies of scale in machinery manufacture, we get

$$C_T = k_T q_R^{\theta} = k_T q_R^{\theta} n^{1-\theta} \quad \text{for } n \text{ machines} \qquad [12]$$

(Note the need to change to a normalised flow $q_R = Q_R / \overline{Q}_A$ to keep the coefficient k_T dimensionally simple.) The elasticity θ is typically 0.55 to 0.7.

Penstock size will depend upon flow and the penstock efficiency η_P we choose. Penstock cost can be shown to have the form

$$C_P = k_P (1 - \eta_P)^{0.4} q_R^{0.8} \qquad [13]$$

Storage costs only arise in the case of intermittent operation. Assuming that storage volume ($d{\cdot}A$) is chosen as a large fixed multiple of penstock volume we can use

$$C_S = k_S C_P \qquad [14]$$

Finally we have civil and electrical costs dependent respectively on flow Q_R and power P_R. As power is proportional to flow and treating all equipment as having the same cost-scale elasticity

$$C_R = k_R q_R^{\theta} \qquad [15]$$

We have in equations [11]-[15] the means of evaluating the changing cost of a system as parameters such as Q_R are varied.

6. Comparison of Options SO, PO and IO

Having optimised the IRR of each of the options by finding the best values for Q_R and other parameters, the three options can be fairly compared. A reference scenario was defined as follows:

$\mu = 0.8$, $\theta = 0.6$, $k_T/k_R = 0.3$, $k_P/k_R = 0.3$, $k_S/k_R = 0.001$

Figure 6 shows the rated flow Q_R, the gross annual income GAI, the capital invested CAP and the relative IRR for PO and IO, taking SO as reference. It can be seen that both PO and IO lead to larger schemes whose internal rates of return are higher than for SO. In the case of intermittent operation IO, the economic advantage is sufficient (10%) to justify considering this alternative. Similar advantage was observed across a representative range of scenarios.

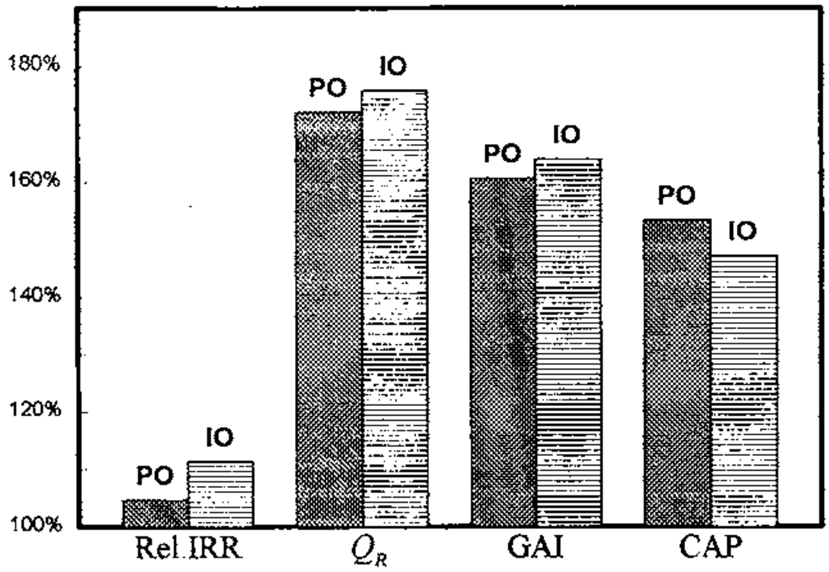

Figure 6. Comparison between IO, PO and SO.

Finally, the effect of varying the different economic and hydrologic parameters is analysed in Ref. 1. One example, relating to the hydrological parameter μ, is shown in Figure 7, confirming that IO and PO are especially attractive for small systems.

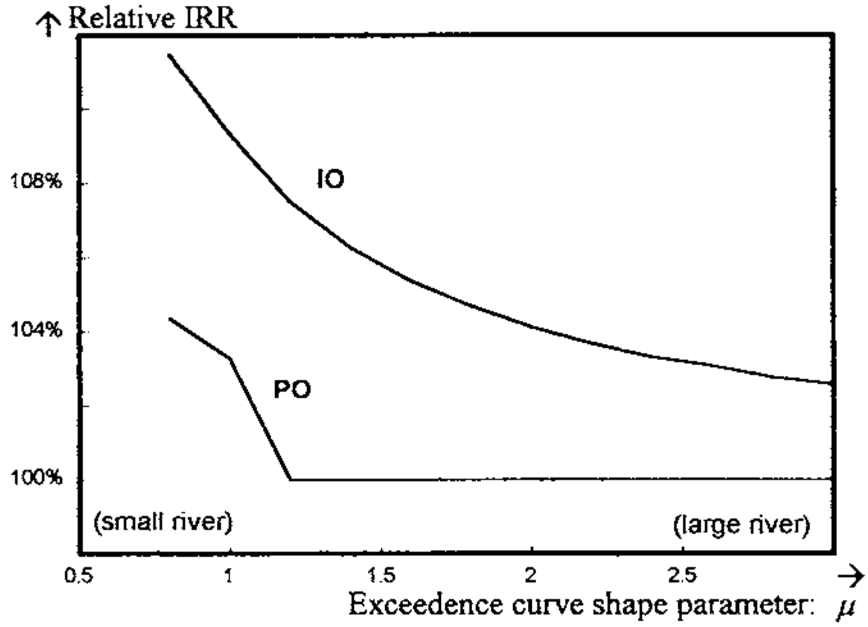

Figure 7. Relative IRR of PO and IO (SO as reference) when varying μ.

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