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Application of Optimal Control to the Determination of an Environmental Levy

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Abstract

This paper is concerned with establishing levies to regulate dam operations to environmentally accepted standards.

We aim to establish a simple mathematical tool that could be used to set "appropriate" levels for the environmental levies which would allow the station operator to remain profitable, yet also to ensure that the operator's policy is environmentally acceptable. We shall use Pontriagin's maximum principle to solve an optimal control problem which will simulate the station operator's behaviour, assuming that their objective is to maximise profits.

The optimal solution will be parametric in the target lake level, target extraction rate, and the levels of the environmental levies. Comparing the simulated time paths of outflow and the lake level over a fixed time horizon with the environmental targets, the regulatory authority can then adjust the levies. In other words, we will investigate the sensitivity of the targets and the degree to which they are satisfied when the levies are altered.

Keywords: *optimal control, environmental levy, hydro-power generation.*

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1 Introduction

In this paper we wish to model a situation where we have an independent hydroelectric power station with its own reservoir[1]. The reservoir might be a natural lake, or an artificial lake, with its own ecosystem. Any water withdrawn from the lake will be discharged into at least one natural water channel. The situation under consideration is one in which (for example) an environmental lobby group has been sucessful in persuading the authority responsible for the regulation of the water system associated to the power station to tax the station operator for environmental damage caused by their reservoir management. In particular we suppose that the levies applied against the power station will be derived from:

- some function of the deviation between the actual rate of water extraction from the target level; and
- some function of the deviation between the reservoir level and the target level.

The target levels here could be determined by some environmental watch-dog, for example, and set in place by the regulatory authority responsible for monitoring the water system.

In general there are two situation to be considered with regard to the levies.

1. If the levies are set too high they could result in the possibility of the operator being forced out of business. If this occured and the power station was therefore no longer in operation then the outflow from the lake would be uncontrolled and the production of electricity would cease. This in itself defeats the purpose of imposing environmental levies to regulate water use in order to achieve environmentally acceptable management by the operator.
2. Alternatively the levies could be set too low and would therefore be ineffective. The operator could then disregard the levy with respect to its water management policy with the possibility of large deviations from the environmentally desired targets occuring, and hence resulting in environmental damage.

We aim to establish a mathematical tool that could be used to establish "appropriate" levels for the environmental levies which would allow the station operator to remain profitable, yet also to ensure that the operator's policy is environmentally acceptable. We shall use Pontryagin's maximum principle to solve an optimal control problem which will simulate the station operator's behavior, assuming that their objective is to maximise profits.

The optimal solution will be parametric in the target lake level, target extraction rate, and the levels of the environmental levies. Comparing the simulated time paths of outflow and the lake level over a fixed time horizon, say a year, with the environmental targets, the regulatory authority can then adjust the levies. If the targets are not being met the levies could be increased. If they are being adhered to by the station operator then a relaxation of the levies might be contemplated, with a view to reducing any unnecessary financial hardship to the operator whilst maintaining an environmentally acceptable solution. Thus we will investigate the sensitivity of the targets and the degree to which they are satisfied when the levies are altered.

The problem which we model in this paper is that of a local authority which would like to enforce some environmental standards and at the same time ensure that enough electricity is generated. The model which we propose will present the authority with a list of options of the environmental levies. Each option may lead to a different trade-off between the *safety of the environment* and the *economic performance* of the power station operators.

[1]This is an extention of the project undertaken by Richard Meade in 1989 for the course QUAN312 at Victoria University of Wellington. The extension was done as a summer reserach project of H.P. Jørgensen, and sponsored by a research grant from the Faculty of Commerce & Aministration, VUW.

2 The Mathematical Model

As mentioned earlier we are considering a single hydroelectric power station drawing water from a reservoir. It is assumed that inflows into the reservoir are known at each point in time, and the only outflow from the reservoir is determined by the operator's extraction of water. Electricity generation is proportional to the water flow, and we assume that the station is not demand-constrained. Thus the relevant constraints are on the supply-side, viz. that the reservoir level must be maintained within some bounds (*i.e.* there will be some minimum required level, and a maximum level before we get spillage from the reservoir), and extraction from the lake will be constrained by the carrying capacity of the stations pipes. Further assumptions are that the revenue per unit, and that the other variable costs, are constant per unit generation.

The operation of the hydroelectric power station is assumed to occur continuously over the period under consideration, and accordingly our analysis will be staged in continuous time. Profits are composed of the net revenue from generation, which is simply proportional to extraction, less the environmental levies imposed by the regulatory authority. Given the deterministic formulation of the system being modelled, the station operator's problem over the time horizon will be to choose that rate of water extraction which will maxamise profits subject to the operational constraints.

Notice that because the resulting optimisation problem is linear-quadratic its *feedback solution* is *certainty equivalent.* That means the optimal solution obtained for the deterministic problem is also optimal for its stochastic augmentation defined as the *expected* profit maximisation subject to the model perturbed by an additive Gaussian noise.

Types of environmental damage that could occur, for which the model should allow, are:

- Reservoir level becoming too low—as in a drought, with obvious environmental damage.
- Reservoir level becoming too high—causing spillage.
- Excess extraction from the reservoir—causing erosion downstream.
- Insufficient extraction from the reservoir—resulting in the upset of the ecosystem downstream.

Notice that these types of damage may be described by the difference between the environmentally desired level, and the actual level. In this context we are refering to a deviation from some target level in the case of the reservoir level, and a target rate in the case of extraction from the lake.

Also notice that the types of environmental damage are interlinked in the fact that the reservoir level becoming too high could be interpreted as an insufficient amount of water being extracted, upsetting the ecosystem downstream. The reservoir level becoming too low could also be interpreted as too much water being released. In this respect deviations from the target extraction rate are intertwined with deviations from the target reservoir level.

The tax for such environmental damage will be applied according to the deviation of the extraction rate from its target rate squared. Thus the larger the deviation, the more the profits that the station operator earns will be affected. The station operator's profits will also be penalised for the deviation of the reservoir level from its target level, again squared, at the end of the fixed time horizon (*i.e.* a year). The logic behind this setup is the fact that the reservoir level and the extraction rate are irrevocably interrelated.

Notice that in using such a construction we need *not* explicitly impose strict upper and lower bounds on the reservoir level and water extraction rate, as the proper imposition of the levies will ensure that the system is driven towards its targets. Assuming the targets are realistic (*i.e.* within these bounds) this tendency will therefore ensure that these constraints are adhered to.

With the following notation we are now in a position to formulate the station operator's problem:

Π	=	profit to the station operator
t	=	time, continuous, range $[0,T]$
$u(t)$	=	control variable: rate of water extraction at time t
$x(t)$	=	state variable: reservoir level at time t
u^*	=	target extraction rate, given
x^*	=	target reservoir level, given
T	=	terminal time, given
r	=	net revenue per unit extraction: difference between unit revenue and variable cost per unit extraction, given
p_1	=	penalty cost factor for deviations from target extraction rate, constant; levy 1
p_2	=	penalty cost factor for deviations from target reservoir level, constant; levy 2
$I(t)$	=	rate of water inflow to reservoir, given
x_0	=	initial lake level, given
s	=	surface area of reservoir, given.

Thus the station operator's problem is to[2]:

$$\max_{u(t)} \Pi = \{\int_0^T \left[ru(t) - p_1(u(t) - u^*)^2\right] dt - p_2(x(T) - x^*)^2\} \tag{1}$$

subject to:

$$\dot{x}(t) = \frac{I(t) - u(t)}{s} \tag{2}$$

where

$$I(t) = a + bcos\frac{4\pi t}{365} \tag{3}$$

and

$$x(0) = x_0 \tag{4}$$

Notice that we assume a simple periodic model for inflow $I(t)$. This corresponds to two peaks and two lows a year. From the point of view of this paper, which concentrates on illustrating the proposed technique, this simplification seems to be acceptable. More elaborate models of the inflow would not change the message of the paper. We now proceed to solve the station operator's problem.

3 The Optimal Solutions

Assume that $T = 1\ year = 365$. Upon applying Pontryagin's maximum principle (see [1] for example) to the problem (1)(2)(3) and (4) we derive the following results.

The optimal state is given as:

$$\hat{x}(t) = x_0 + \left[\left(a - u^* - \frac{r}{2p_1}\right)\frac{sp_1}{Tp_2 + p_1s^2} - \left(\frac{p_2}{Tp_2 + p_1s^2}\right)(x_0 - x^*)\right] t + \frac{365b}{4\pi s}sin\frac{4\pi t}{365} \tag{5}$$

The (open-loop) optimal control is:

$$\hat{u}(t) = \frac{1}{Tp_2 + p_1s^2}\left(p_1s^2u^* + Tp_2a + \frac{rs^2}{2} + p_2s(x_0 - x^*)\right). \tag{6}$$

Notice that since $\hat{u}(t) = \hat{u}$ is constant it is very easy to derive the expression for the performance index which is:

$$\Pi = \left[r\hat{u} - p_1(\hat{u} - u^*)^2\right] 365 - p_2(\hat{x}(365) - x^*)^2. \tag{7}$$

In Section 5 we will simulate the operation of two chosen New Zealand dams using the expressions (5), (6) and (7).

[2]Area s is measured at some average level.

4 New Zealand Dams

In order to illustrate the proposed technique of adjusting the levies to given targets, and to test the mathematical model and the optimal solutions that have been derived from it we shall look at two New Zealand dams. These two dams fulfill the basic requirements of our model in the fact that they all have their own reservoir and the outflow from each reservior is being discharged into at least one natural, or artificial, water channel. The dams that shall be looked at are both in the North Island and are the Karapiro Dam and the Matahina Dam.

With the datum that was collected with respect to these two dams[3] we were able to derive the inflow function for each of the dams, as well as the average reservior level (which we will use as our initial reservior level), and the net revenue figures. Please note that in reality a hydroelectric power station has a spillway. As our model does not incoorporate this feature, since we assume that all outflow from the reservior is used for the production of electricity, our net revenue figures for each of the dams will be lower than they are in actuality.

The relevant variables for the dams in question are as follows:

The Matahina Dam

$$\begin{aligned} I(t) &= 4\,838\,400 + 846\,720 cos\tfrac{4\pi t}{365} \;\; [m^3/day] \\ x_0 &= 75.9 \;\; [m] \\ s &= 2\,480\,000 \;\; [m^2]; \end{aligned}$$

The Karapiro Dam

$$\begin{aligned} I(t) &= 18\,921\,600 + 2\,203\,200 cos\tfrac{4\pi t}{365} \;\; [m^3/day] \\ x_0 &= 56.7 \;\; [m] \\ s &= 7\,700\,000 \;\; [m^2]. \end{aligned}$$

Notice that now the optimal solutions (5), (6), (7) are, for each reservoir, functions of the levies p_1 and p_2 only.

5 The Results

We shall now assume that an environmental lobby group has been sucessful in persuading the authorities responsible for the regulation of the water systems associated to the hydroelectric power stations that some sort of environmental levy should be applied to the power stations. The sole purpose of this levy, or levies, being to penalise the station operator's profits for any environmental damage caused by their reservoir management.

Let us assume that some independent body conducts an inquiry into what the environmentally acceptable reservoir levels and outflow rates should be. This group then, in effect, is determining what the values of x^* (and possibly u^*) should be for our model. The finding of the independent body would then be submitted to the authorities responsible for the regulation of the water systems used by the power stations. This authority could then use the optimal solutions derived from this model to see what sort of impact varying levies would have on the actions of the hydroelectric power stations with regard to the reservoir level over time and the extraction rate from the reservoir in question.

For simplicity we shall initially set $x^* = x_0$ and u^* equal to the average daily inflow, so that the dams under consideration are initially in "equilibrium". We shall then proceed to derive values for p_1 and p_2 which result in the same amount of profit being produced, on average, by the dams. By doing this we are, in effect, not controlling the system, yet setting lower bounds

[3]The data was supplied by Electricorp Corporation of New Zealand Ltd. see [2].

for the values of our two levies. The results will be presented in the form of tables, the first row of which will always correspond to the basic set of the models parameters (called equilibrium).

5.1 The Matahina Dam

The approximate profit after tax for the Matahina dam is $NZ 3 743 866 (data of 1990, see [2]). Initial parameters that yield that approximate profit for the Matahina Dam are:

r	0.002 119 950 4 $[\$/m^3]$
u^*	4 838 400 $[m^3/day]$
x^*	75.9 $[m]$
p_1	0.001 $[\$/m^6/day]$
p_2	0.001 $[\$/m^2]$

We now proceed to shock this equilibrium system in order to see what happens to our relevant parameters and to see how the lake level can be maintained, if need be, through use of the levies.

1/ Firstly we shall increase the desired level of outflow, u^*. The reasoning behind this could be an increase in demand for electricity (for white water rafting) which the dam operator responds to by increasing the desired outflow level.

Table 1 shows that increasing u^* by 1% results in an increase in the optimal outflow $\hat{u}$ of 1%, an increase in after tax profits of 1%, and a decrease in the lake level of 10%. That might be too much for the environment to cope with. Our algorithm indicates that an increment of p_2 up to 1.2 million NZ$ per m^2 is still not enough to bring the lake lavel back to some tollerated deviation from the target. Moreover, the penalty for not sticking to the outflow target u^* make the dam operation almost unprofitable. Having relaxed that penalty ($p_1 = 10^{-6}$) brings the lake to an acceptable level; and it should still be profitable for the operator to run the dam.

parameter: r	p_1	p_2	x_0	x^*	u^*	$\hat{x}$	$\hat{u}$	Π
.00211995	$1*10^{-3}$	$1*10^{-3}$	75.9	75.9	4838400.	75.9	4838410	3743867
.00211995	$1*10^{-3}$	$1*10^{-3}$	75.9	75.9	4886780.	68.8	4886790	3781310
.00211995	$1*10^{-3}$	$1.2*10^{6}$	75.9	75.9	4886780.	69.3	4883570	4681
.00211995	$1*10^{-6}$	$1.2*10^{6}$	75.9	75.9	4886780.	75.8	4839080	2913940

Table 1: Consequences of the changes of u^*.

2/ Table 2 shows that an increase (or decrease) in r of 10% results in an increase (or decrease) in the after tax profit of the dam operator of 10%, and the reservoir level and outflow are for all practical purposes unaffected.

3/ Now we increase x^*. This is where primary concern should be focused as the report from the environmental group may in fact advise an increase in the reservoir level as being beneficial to the environment overall. The mechanism of the changes will turn out to be smimilar to that in 1/.

Table 3 shows that by increasing x^* by 0.5 m (which is 0.7 %) to 76.4 and maintaining all other parameters constant the system remains in its initial 'equilibrium'. That is, none of the other parameters, except for x^*, change. Our environmental levies must therefore be used in order to induce the system to alter.

parameter: r	p_1	p_2	x_0	x^*	u^*	$\hat{x}$	$\hat{u}$	Π
.00211995	$1 * 10^{-3}$	$1 * 10^{-3}$	75.9	75.9	4838400.	75.9	4838410	3743867
.00233195	$1 * 10^{-3}$	$1 * 10^{-3}$	75.9	75.9	4838400.	75.9	4838420	4118270
.00190795	$1 * 10^{-3}$	$1 * 10^{-3}$	75.9	75.9	4838400.	75.9	4838401	3369490

Table 2: Consequences of the changes of r.

parameter: r	p_1	p_2	x_0	x^*	u^*	$\hat{x}$	$\hat{u}$	Π
.00211995	$1 * 10^{-3}$	$1 * 10^{-3}$	75.9	75.9	4838400.	75.9	4838410	3743867
.00211995	$1 * 10^{-3}$	$1 * 10^{-3}$	75.9	76.4	4838400.	75.9	4838410	3743867
.00211995	$1 * 10^{-6}$	$1 * 10^{-3}$	75.9	76.4	4838400.	75.4	4839460	3744280
.00211995	$1 * 10^{-6}$	$1 * 10^{6}$	75.9	76.4	4838400.	76.39	4835080	3487110

Table 3: Consequences of the changes of x^*.

Firstly we decrease the penalty for the desired outflow deviating from actual outflow so that the dam operator is not penalised for lowering the outflow of water, and hence raising the reservoir level. However, this will even lower the reservoir level since the operator is tempted to keep $\hat{u}$ hight since this keeps their profit hight. So we have to increase p_2. After it has been increased to $1 * 10^6$ a reasonable level of profit has been achieved as well as the target lake level met.

Now we will apply our technique to discuss the levy values for the Karapiro dam.

5.2 The Karapiro Dam

The approximate profit after tax for the Karapiro dam is NZ$7 132 921. Initial parameters that yield this profit for the Karapiro Dam are (see [2]):

r	0.001 032 8 [$\$/m^3$]
u^*	18 921 600 [m^3/day]
x^*	56.7 [m]
p_1	0.001 [$\$/m^6/day$]
p_2	0.001 [$\$/m^2$]

We now proceed to shock this equilibrium system in order to see what happens to our relevant parameters and to see how the lake level can be maintained, if need be, through use of the levies.

1/ Firstly we shall increase the desired level of outflow, u^*. The reasoning behind this could as above *i.e.* be an increase in demand for electricity (or white water rafting) which the dam operator responds to by increasing the desired outflow level.

Table 4 shows that increasing u^* by 1% results in an increase in the optimal outflow $\hat{u}$ of 1%, an increase in after tax profits of 1%, and a decrease in the lake level of 16%. This will be too much for the environment to cope with. Our algorithm indicates that a sole increment of p_2 up to 17 500 NZ$ per m^2 is still not enough to bring the lake lavel back to some tollerated deviation from the target. Having relaxed the penalty for not adhering to u^* ($p_1 = 10^{-14}$) brings the lake to an acceptable level. Also, running the dam is profitable.

parameter: r	p_1	p_2	x_0	x^*	u^*	$\hat{x}$	$\hat{u}$	Π
.0010328	$1*10^{-3}$	$1*10^{-3}$	56.7	56.7	18921600	56.7	18921600	7132921
.0010328	$1*10^{-3}$	$1*10^{-3}$	56.7	56.7	19110800	47.73	19110800	7204240
.0010328	$1*10^{-3}$	$1.75*10^{4}$	56.7	56.7	19110800	49.8	19005600	3704480
.0010328	$1*10^{-14}$	$1.75*10^{4}$	56.7	56.7	19110800	56.47	18926400	6836250

Table 4: Consequences of the changes of u^*.

2/ Table 5 shows that an increase (or decrease) in r of 10% results in an increase (or decrease) in the after tax profit for the dam operator of 10%, and the reservoir level and outflow are for all practical purposes unaffected.

parameter: r	p_1	p_2	x_0	x^*	u^*	$\hat{x}$	$\hat{u}$	Π
.0010328	$1*10^{-3}$	$1*10^{-3}$	56.7	56.7	18921600	56.7	18921600.5	7132921
.0011361	$1*10^{-3}$	$1*10^{-3}$	56.7	56.7	18921600	56.7	18921600.6	7832401
.0009295	$1*10^{-3}$	$1*10^{-3}$	56.7	56.7	18921600	56.7	18921600.4	6419621

Table 5: Consequences of the changes of r.

3/ Now we increase x^*. This is where primary concern should be focused as the report from the environmental group may in effect advise an increase in the reservoir level as being beneficial to the environment overall.

Table 6 shows that by increasing x^* by 0.5 m (which is 0.88%) to 57.2m and maintaining all other parameters constant the system remains in its initial equilibrium. That is, none of the other parameters, except for x^*, change. Again, our environmental levies must therefore be used in order to induce the system to alter.

parameter: r	p_1	p_2	x_0	x^*	u^*	$\hat{x}$	$\hat{u}$	Π
.0010328	$1*10^{-3}$	$1*10^{-3}$	56.7	56.7	18921600	56.7	18921600	7132921
.0010328	$1*10^{-3}$	$1*10^{-3}$	56.7	57.2	18921600	56.7	18921600	7132921
.0010328	$1*10^{-11}$	$1*10^{-3}$	56.7	57.2	18921600	0	70516200	16886300
.0010328	$1*10^{-11}$	$1.75*10^{4}$	56.7	57.2	18921600	57.0	18915800	1011280

Table 6: Consequences of the changes of x^*.

Using the arguments similar as in the case of the Matahina Dam we conclude that there exists a pair of (p_1, p_2) (namely, $p = 10^{-12}$, $p_2 = 1.75\,10^4$) which allows a reasonable level of profit from this dam operation as well as keeps the related environmental damage under control.

6 Concluding Remarks

In this paper, we have introduced a simple one-reservoir optimisation model. Based on that model, we have built an interactive computer programme which enables us to both:

- vary the model parametres which are responsible for the natural and economic environment within which the reservoir operates, and
- to watch the model changes due to those variations.

In effect, we have been able to indicate what are the values of parameters, identified as the *environmetal levies*, which would guarantee the sound natural environment and the profitable operation of a dam.

It should be noted that by applying the environmental levies the outflow derived for the dam operator is optimal in the sense that is detrimental for him not to follow the advised policy.

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