Journal of Economic and Social Policy

Volume 14
Issue 3 *Current Issues in Regional Australian Economic and Social Policy*

Article 7

10-19-2011

Economic Modelling of Climate Change and Water in a Regulated River Basin

Jerry Courvisanos
University of Ballarat

Colin L. Richardson
Imperial College London

Recommended Citation

Courvisanos, Jerry and Richardson, Colin L. (2011) "Economic Modelling of Climate Change and Water in a Regulated River Basin," *Journal of Economic and Social Policy*: Vol. 14 : Iss. 3 , Article 7.
Available at: http://epubs.scu.edu.au/jesp/vol14/iss3/7

Economic Modelling of Climate Change and Water in a Regulated River Basin

Abstract
Focus is on agricultural production of a river basin economy and ecosystem processes relating to climate change and water supply. A generic regulated river basin model of agricultural production is integrated with an existing demand-based macroeconomic model in discrete time which has been developed previously over a series of computer simulation experiments. This is the forerunner to a fully-specified Murray-Darling Basin model. Two crops are in the model - rainfed wheat and irrigated rice - with River Basin Commission revenue and expenditure, as well as exports and imports outside the river basin economy. The model simulates 100 years of production.

Keywords
Complexity modelling, deterministic ecological system models, sustainable development, computer simulations, Post Keynesian economics

Cover Page Footnote
With appreciation to the valuable contributions from participants at the presentation of an early version of this paper at the Eighth Society of Heterodox Economists, Conference, University of New South Wales, Sydney, 7-8 December, 2009

Introduction

There is currently no agreed methodology for diagnostic projection of the impact of government policies and business strategies on the evolution of a regional economy that comprises a *regulated river basin* economy, including crucial ecosystem services, especially water.[1] Without this, it is not possible to identify sustainable solutions to challenges currently facing such a river basin economy and its environment. This is of particular concern with the Murray-Darling River Basin, the source of inland water for the food bowl of Australia. At the heart of the problem is the lack of a non-equilibrium modelling approach with appropriate policy levers; one that embraces the complexity of interactions at the individual sector level within the basin, and can also be linked to ecological models of sustainability.

This paper reports on the first exploratory step in developing a non-equilibrium modelling approach to what eventually will become a fully-specified and policy-oriented model of the Murray-Darling Basin (MDB). An over-simplified generic regulated river basin supply-based model of agricultural production is integrated with an existing non-equilibrium demand-based macroeconomic model disseminated by the authors over a series of computer simulation experiments in previous published papers.[2]

In this economy-ecology model, the focus is on agricultural production in the river basin and the ecosystem processes relating to climate change, water supply and carbon emission. These supply-based concerns are linked to demand for the crops and the necessary capital goods (investment) in the river basin economy. The final version will have a ‘front end’ with a real-time interactive graphical interface for displaying the resulting spatio-temporal data, allowing users to adjust

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[1] In regulated river basins, the rate of flow and release of water is totally controllable. The ecological part of the model developed in this paper is grossly simplified because it eventually will be replaced by the best existing biophysical model of the specific regulated Murray-Darling Basin.

[2] Michał Kalecki and John Maynard Keynes contemporaneously and independently devised effective demand macroeconomic models to address the problem of major business cycle contractions of the type that emerged in the 1930s Great Depression. It is to this tradition of Post Keynesian Economics that the previous simulation modelling experiments by the authors belong (see Courvisanos and Richardson, 2006; Richardson and Courvisanos, 2008).

policy levers and immediately observe the short, medium and long-term consequences for the economy and ecology of the basin.

Theoretical Approaches

Computable general equilibrium (CGE) economic models currently are used to inform policy in regulated river basins. Their advantage is that they can simultaneously model a large number of sectors of the economy and can be relatively easily and quickly solved. The CGE approach reflects the mainstream neoclassical economic agenda of breaking down the economic system into optimal decision-making actions that tend towards some equilibrium. This optimal decision-making model incorporates the 'value of waiting' in the investment decision function to avoid downside risk in revenues over the uncertain future, while sacrificing profit flow by postponing viable investment projects (Dixit, 1992; see also Dixit and Pindyck, 1994). Using this conventional approach, even fundamentally uncertain processes[3] (e.g., investment in plant and equipment that depends on a certain significant amount of water being available at the right times) can be decomposed into their elements to derive an optimal balance between the decision to invest or wait for more information before investing. This balance (or equilibrium) can be modelled 'organically' in a series of comparative static changes over logical (ahistorical) time.

The disadvantage of this mainstream neoclassical approach is that it cannot predict temporal behaviour of the economy over timescales shorter than those associated with reaching equilibrium. There is no way of analysing or projecting what happens from one notional equilibrium position to another equilibrium position sometime in the non-defined future. However, in order to display time-series graphs of the system's responses to a set of (typically supply-side) 'shocks', time is smuggled in using units like months, quarters, years, or 'periods', implying that the economy reaches a fresh equilibrium every month, quarter, year, or 'period' But this appeal to ahistorical time is mere assumption or, worse, wishful thinking. Real-world policy makers need more; they need to see the sequence of simulated data-points traced out by the model economy as it traverses between each pair of these 'equilibria'.

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[3] The economics literature refers to such process as 'non-ergodic' (see Davidson, 1991).

The dynamics of the system are particularly important where ecosystem processes are either drivers of the economy (e.g., ecosystem services like river-water flows) or are impacted by economically-motivated policy (e.g., pricing policy in respect of water resources). In these cases it is unlikely that the ahistorical equilibrium timescales associated with the dynamics of the economy will coincide with the historical-time ones relating to ecosystems. The latter have much longer timescales for investigation compared to the former. Indeed most ecosystems are always in traverse, never in equilibrium. Therefore, it is not possible using CGE modelling to *simultaneously* envisage the impact of policy on the environment and the economy, which is a necessary modelling step in the development of guidelines for sustainable policies (Ayers, 2008).

The only way to properly couple economic and ecosystem models is for them both to be dynamically determined in an integrated non-equilibrium model. However, there is as yet no economic modelling methodology available that is able to accommodate a sufficiently large number of sectors simultaneously, and simulate a regional economy's complex temporal evolution. By contrast, there is a wealth of biophysical models that are capable of forecasting the dynamical behaviour of complex ecosystems in simulated historical time. There is, therefore, an opportunity to redress the balance and develop the most appropriate complex economic model with ecosystem sustainability. Recent advances in non-linear and complex systems theory offer new possibilities for building such a regional model. These emerging possibilities, along with novel approaches for seeking target solutions, make this an opportune moment to seize this opportunity.

This paper outlines the first modelling attempt at fully incorporating the two sides of the economic equation, demand and supply, in an ecological setting. On one side, there is a dynamic non-equilibrium macroeconomic model dependant on effective demand to determine economic activity (or Gross Domestic Product) scenarios based on specific supply-based conditions. On the other side, there is a simple ecosystem model that frames and simulates the natural environment within which supply of agricultural production is realised. An integration of both sides is modelled in an effort to simulate effects on sustainability of different ecological and economic policy packages.

The modelling begins with an alternative economic approach developed from research in dealing with fundamental uncertainty as an epistemic instability of beliefs, reinforced and magnified by institutional features in financial markets and technological change (Runde, 1991). Behavioural motivation is modelled in this approach to decision-making which underlies economic instability. This results in a non-equilibrium open system based on historical (real) time processes with cumulative causation and accompanying path dependence in the system's evolution. Further, Lerch and Nutzinger (2002) argue that the dangerous and irreversible processes associated with investment in capital goods since the Industrial Revolution have created fundamental uncertainty around the ecological sustainability of this planet, which requires *homo oeconomicus* "…to deal with the shaping of the frame conditions' rather than 'merely react to these conditions". It is this objective that the economic modelling exercise described here is addressing.

The investment decision-making dynamics in this approach originate with the work of Michał Kalecki on investment cycles and increasing risk, in which profits derived from effective demand provide both the ability and the incentive to invest (Kalecki, 1939). Kaleckian foundations deliver an investment cycle of corporate instability due to entrepreneurial uncertainty. To manage such uncertainty, decision-making agents work with conventions and rules that are sensitive to information about the unknown future and evolutionary processes of technological innovation. Courvisanos (1996) synthesises this alternative analysis by identifying susceptibility of investment as the sensitivity factor. Courvisanos and Richardson (2008) detail an exposition of a macroeconomic simulation model built along these Kaleckian lines to map out various types of economic development paths that emerge from different innovation and investment regimes. This is the basis of the approach used to build the model described in this paper.

The modelling begins with Kaleckian investment specifications from Courvisanos and Richardson (2008), but adapted to the production of two agricultural products, rainfed wheat and irrigated rice, grown in a hypothetical regulated regional river basin. In this exploratory model, the two crops are indicative only, and the river basin is a generic region which is not specified in terms of any real ecosystem.

From the regional perspective on the environment, conventional market failures are (or are attempted to be) resolved by broad National and State Government centralised interventions. However, these come up against systemic failure due to entrenched individual regional interests that militate against the required social cohesion and ecological awareness which make such interventions successful. Market failures are handled by establishing (often after so-called 'community consultation') optimal equilibrium-based modelling with centralised 'top-down' adjustments to incentives, regulatory responses and improved information provision. All such actions can be useful, but regional interests (that can often be divergent) cannot be integrated so as to progress towards a long-term community strategy.[4]

Using conventional approaches with market failure as the driver has resulted in the traditional tension between production and environmental protection. This has been challenged by alternative complexity-based economic approaches that identify ways for the economic and the ecological to develop together in a new synthesis (Ayres, 2008). Using complexity analysis modelling, after Courvisanos and Richardson (2006), the generic river basin model makes an ideal test bed for the evolution, investigation and trial simulations of a new synthesis of economics and ecology that does not have the same traditional tensions. For this reason, the approach to modelling developed here aims to significantly enhance current efforts by policy makers, agriculturists and environmentalists to better plan and manage the MDB. In this way, this simulation exercise provides a particularly appropriate and timely research focus to issues on climate change and water. Although the development of the model described in this paper is a purely technical modelling activity, the objective is to challenge the mainstream approach to addressing the economic-ecological dilemma. This locates the modelling exercise adopted here within the radical political economy agenda.

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[4] This problem can be evidenced by a quote from a mainstream neoclassical economics study that argues "…that there is *at least theoretical* support for the notion of an *optimal* level of effort to devote to any community consultation activity" (Crase et al., 2005, p. 235, emphasis added).

The Model

The generic river basin model presented in this paper is based on previous dynamic non-equilibrium macroeconomic models, as noted above. The fundamental driver in such models is the 'profitability gap' that provides all the incentive, and a crucial part of the finance, for businesses' investment demand for new capital formation. This makes net investment positive (negative) when the expected profit rate is greater (less) than the normal or 'hurdle' profit rate, and increases accumulation (decumulation) as the profitability gap becomes more positive (negative) (Richardson and Romilly, 2008). The model remains 'stable' in the dynamic sense that, although numerically large shocks to its parameters cause gross changes away from 'normality' (which turns out to be four regular cycles over a century of simulated historical time), they do not make the river basin economy collapse, send endogenous variables spinning off to infinity, or switch to a chaotic regime. This robust character is likely due to the model not having any commodity or finance supply-demand equations determining flexible prices via iteration, apart from the money wage rate. These are considered reasonable assumptions for a relatively small regional agricultural economy facing exogenous export prices and sourcing almost all its domestic commodity absorption from the Rest of Australia.

This first iteration of a generic river basin agricultural model has only two annual crops, with independent sub–models for rainfed wheat and irrigated rice[5]. Potential conflicts exist with both crops; e.g., rice can hit a regulated irrigation constraint, thus favouring wheat; while wheat can hit a natural rainfall constraint, thus favouring rice. Both crops can hit a land constraint, with the crop promising higher expected profitability winning out in the competition to secure more arable acreage. Initial export prices for rice and wheat are established, and both rise with every year, as do domestic prices for local irrigation water and such imports as seed and fertiliser.[6] The irrigation water price also increases as a water scarcity index rises with the cultivation of more land for rice. This is the simplified form

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[5] Perennial crops and livestock will be added in later iterations, as they are important primary production activities in the Murray-Darling Basin.

[6] There is only one irrigated crop (rice), so there can be no trading with other irrigated crops in this iteration of the model. Also, the model represents all rice growers as operating in a single region, with no sub-regions for trading water between rice farmers in different locations.

in which the ecosystem and environmental constraints will appear until one of the existing comprehensive MDB biophysical models, described later, replaces them. These land, irrigation water, and rainwater constraints all bind during the particular model experiment run reported in this paper. The River Basin Commission (RBC) is the region's 'government', which finances its expenditure by 'taxing' irrigation water inputs and carbon emissions, while running a balanced budget.

Each of the two crop sub-models contains some 45 equations and identities, plus eight constants. The macroeconomy section contains 71 equations, identities and constants, with 178 substantive rows in the entire spreadsheet. There are columns for Year -1, Year 0, and also for Years 1, 2, 3, …, 100, with the first two years (-1 and 0) needed to insert the initial conditions of the region's ecology and economy, as given by its soils, climate, rainfall, opening prices, and prior history of human settlement and agricultural production. The key mathematical relationships in the computer model of the river basin economy are set out in Appendix A.

The money wage rate flexes with domestic inflation, labour productivity growth and the ratio of employment to workforce, while never falling below the previous year's level. Credit is in perfectly elastic supply, sourced from outside the river basin economy, thus the interest rate remains constant at 3.7 per cent per annum (p/a). The initial export prices of rice and wheat both rise by 1.2 per cent p/a and all initial import prices for seed, fertiliser and etc. increase by 1 per cent p/a. Although the Irrigation Water Price grows at 1 per cent p/a (plus the percentage rise in a Water Scarcity Index as mentioned above), the RBC policy makers can experiment with different prices. Water and carbon prices that can be regulated by the RBC represent important policy levers for reacting to climate change, water shortages and declines in water quality.

Most of the spreadsheet rows contain identities, i.e., relationships which are true by definition, performing a similar role to the conservation laws in physics. The essence of the model is the minority of equations (with their constants) which mimic nature, technology and economic behaviour. This is as it should be: models are supposed to explain much by little. It is assumed there exists within Australia a hypothetical river basin whose area is 295,000 hectares (ha) of land, suitable for farming either rainfed wheat (annually 236 gigalitres (Gl) of Normal Rainfall, but only 200 Gl of Actual Rainfall) or irrigated rice (annually 660 Gl of Potential Irrigation Water) or both. The latter remains a theoretical limitation for most of the simulated century, as the RBC is not in a position to build enough infrastructure (dams, weirs, and barrages) to realise the basin's entire 660 Gl annual irrigation potential until sufficient rice farms have been established by private enterprise investment. The two crops are exported in their entirety to either the Rest of Australia (RoA) or the Rest of the World (RoW), with farmers obtaining the same export prices at the farm gate, no matter which market their harvests are sold into. They also import all their farming inputs (except water and labour) from RoA and RoW, together with all commodities consumed by farmers' and workers' families. In Year 1 of the 100+ years of historical time that the river basin has been cultivated, there were 23 rice and 25 wheat farms, of the minimum economic size (MES) of 3,000 ha and 1,400 ha, respectively. After a century (and four economic cycles), there are 52 rice and 92 wheat farms in Year 100.

Farmers do not necessarily plant all their available farm area; each obeys the profitability gap investment equation determining the number of hectares planted each year. Dividing by MES gives the number of standard farms, of which the latest one purchased might have to be only partly planted. Inputs of seed, fertiliser, and water depend on the number of hectares, while the Fixed Assets Rental Bill depends on the number of standard farms. Leasing all farm assets (farmhouse, outbuildings, silos, and machinery) from outside the river basin removes any need for modelling the supplying industries, and for recognising capital depreciation in the farm accounts. However, the profitability gap equation also determines 'Wheat Land Investment' and 'Rice Land and Water Investment', with these values accumulating into stocks of non-depreciable assets, i.e. purchase of farmland plus spending on improvements, together with private irrigation infrastructure in the case of rice.

There are no neoclassical production functions, hence no factor substitution – apart from that driven by technical progress – among land, other assets, seed, fertiliser, water, or labour. Crop Yield (in tonnes per ha) grows with the sum of 'Land and Water Investment' and 'River Basin Commission Expenditure' on agronomy research, and agricultural extension. When multiplied by Area Planted (in ha), Crop Yield sets the harvest size (in tonnes). The River Basin Commission (RBC) is the region's 'government', which finances its expenditure by 'taxing' irrigation water inputs and carbon emissions, while running a balanced budget. Labour Productivity (LP, in tonnes per worker) grows at fixed rates; when divided by LP, the harvests of Rice (and Wheat) Produced determine the respective levels of Employment (in workers).

In the farm accounts for each crop, interest-bearing debt is calculated by adding the annual bills for wages, seed, fertiliser, fixed asset rentals, water, and emissions to 'Land and Water Investment' (all of which are financed by borrowing at the start of each year), then subtracting Savings by Farmers. This is then divided by Capital Turnover (2 times per year), yielding the Average Debt from which their annual Interest Bill is calculated using the exogenous Interest Rate. The Average Equity of farmers is computed by subtracting Average Debt from their Farms Asset, which comprises the current Crop-in-Field's value and all Land and Water Investments accumulated to date. This provides data to form the time series of Debt:Equity Ratios; this will prove a significant explanatory variable in the next iteration of this river basin model, though at present the Debt:Equity Ratio has no substantive role.

Savings by Farmers is 27 per cent of their income, comprising realised Profit (less Interest Bill), with the remainder being spent on Consumption of imported goods and services. Savings by Workers is only 2 per cent of the economy's Wage Bill, as fieldhands have to spend most of their income to support their families' Consumption imports. To avoid the 'Pasinetti Paradox' of workers eventually outsaving capitalists and taking over their role (Moore, 1974; Lavoie, 1998), there is the assumption that these fieldhands do not buy shares in farms, but deposit all their savings (i.e., as a kind of privately-financed unemployment insurance) in the same banks which lend money to farmers as each crop year opens.

The arable land, along with the level of normal rainfall and potential irrigation water, are fixed in the river basin economy. As a matter of prior history, the economy starts in Year 0 with only 35 per cent of the arable land being utilised. This allows for growth in land utilisation with a steady workforce growth rate of 0.7 per cent p/a. In Year 1 the simulation exercise begins. What propels the simulation every year is the existential fact that, in the non-ergodic world of reality, farmers' static expectations of future profitability are *not necessarily realised* at the yearly harvest/sale time. If the land constraint binds, the crop having the larger expectation of profitability by its farmers obtains all the arable acreage it wants and the balance is left for the other crop. Otherwise, each set of farmers purchases all the land demanded. The two sets of crop farmers face normal profit rates comprising the common interest rate plus a crop-specific risk premium. Thus, there can be a ‘profitability gap’ or wedge between expected return on capital and opportunity cost of capital. As this gap widens and narrows, so the river basin economy expands and contracts in terms of land utilisation. The simulation exercise is allowed to run for 100 years. The complete Excel sheet with the century-long simulation run can be obtained from the authors. Significant model results are outlined in the next section.

Model Results

Some of the more significant results of the simulation exercise are presented as graphs in Appendix B. Figure 1 shows the extent of the fixed arable land planted (or utilised) p/a for wheat and rice. Two points of interest arise. One is that the planted areas for wheat (Aw) and rice (Ar) fluctuate, which then reflects on total production (real GDP or Yr). The second is that as land utilisation (A) reaches full arable capacity (AE) by the end of the century, rain fed wheat crop planting finally overtakes the near-century domination of irrigated rice crop planting in relation to the total land utilised. This contrasts with a run of the model having no ecological constraints; this showed Ar maintaining its dominance throughout the century without Aw closing the gap. Thus land scarcity makes the non-irrigated crop the more favoured of the two.

Figure 2 displays the economic variables that register the outcome of crop production. The mild real GDP business cycles in earlier years eventually develop into cycles having greater amplitude towards the latter part of the century. Unrealistically, the century ends with a massive recession as Yr contracts by nearly 48 per cent from a peak in Year 92 to the trough of Year 99. This is due to the model not yet having been subject to fine tuning that can ‘regularise’ the business cycles. The model’s next iteration likely will retain some degree of increasing cyclical volatility, though the actual extent cannot yet be specifically quantified.

Figure 3 merely *tracks* the endogenous debt-to-equity (D:E) ratio, in readiness for making it (in this model's next iteration) an important Kaleckian influence on shaping investment in capital stock. Along with the profitability gap, the D:E ratio then will help drive the kind of business cycles identified in Figure 2.

The impact of the profitability gap and consequent business cycles can be seen in Figure 4, which shows how these cyclical movements affect total employment (L) in the two crop production processes (Lw and Lr). While L is shown above the available workforce (N) at all four cyclical peaks, this is quite realistic for the first two cycles, as overtime working is common in farming practice. In the last two (unrealistic) cycles, the extreme situations shown will be corrected in the next iteration of the river basin model.

In Figure 5, the real wage rate cycles are common to both crops, given that generic 'fieldhands' work on both types of farms. The prime cost (PCr) and export price (Pr) of rice are consistently lower throughout the century than the prime cost (PCw) and export price (Pw) of wheat, but it is *relative* profitability that matters. The fact that water scarcity and RBC 'taxes' impact more heavily on the irrigated rice crop than on the rainfed wheat crop is evident from the smaller 'zone of profitability' under the price line (PC < P) of rice, relative to wheat.

Figure 6 reflects the cyclical effects identified in Figure 2, in terms of the profit rates for rice (rri) and wheat (rw). These intensify the volatility and amplitude of the production and GDP cycles, driven as they are by real investment which, in turn, is determined by the sequence of profitability gaps between cycling profit rates and the constant interest rate, adjusted for risk. Due to fine tuning being reserved for the model's next iteration, the last two troughs in the profit rate reach significant negative territory for wheat in the late 60s - early 70s of the fictional century, and again at the end of that century. Irrigated rice has lower volatility than rainfed wheat due to (a) rice farmers reacting less than wheat farmers to profitability gaps, and (b) the RBC's water 'taxation' of rice production. The tax-reduced profitability of rice lowers its profitability gap relative to that of wheat, thus ameliorating the former crop's cycles.

Figure 7 depicts business cycle dynamics of the river basin economy through the unemployment rate (u) and the capital-output ratio (v). The unemployment rate shows a delayed (or hysteresis) effect of expansions and contractions. Thus, in the first 70 years when the cycles were mild, the unemployment rate did not go above 8.6 per cent (Year 52), but with the recession trough of Year 77 the unemployment rate reached 24.7 per cent (Year 79) and in the trough of Year 99 it reached 37.1 per cent (Year 100). This pattern is closely matched by the capital-output ratio, but with less variability. For the first 30 years, this capital-output ratio does not decline, reflecting the strong growth in capital goods *vis-à-vis* output, and the productivity of capital stock falling. As the capital-output ratio declines in the 30s, unemployment falls. Both are reversed in the 40s decade. These patterns recur through three peaks (Years 52, 77 and 99) and two troughs (Years 65 and 89), but with greater variability. Notably in the 90s cyclical contraction, the output fall is lower than the capital stock fall, so that the capital-output ratio rises. Lower capital stock weakens future ability to rebound from a contraction and entrenches unemployment unless there is significant investment in new technological capital.

Figure 7 also shows the export price index (px) rising steadily above the domestic price index (p), and the exogenous inflation rate of px (1.2 per cent p/a) exceeds that of p (1.0 per cent p/a). Further, the Water Scarcity Index for wheat (hsiw) became a severe constraint in the second half of the century, reaching 1.00 in Year 92 after starting in Year 0 with an index number of 0.2401. This reflects the serious nature of water scarcity in the model, clearly linking the economic variables to the ecological variables. This ecological pressure is evident in the fact that the land utilisation ratio (a) of 35 per cent in Year 0 reached 100 per cent in Year 88, remaining there up until Year 97, after which it fell back to 95 per cent by Year 100 due to the contraction of GDP (Yr) as seen in Figure 2. It is interesting to note that the reduction in land utilisation began in Year 98 despite the contraction starting in Year 93 – another hysteresis effect as demand remains high even though it comes off the large peak of Year 92. Impact on land utilisation does not occur for another six years (in Year 99), and then by only one per cent.

Implications

Despite this being the first iteration of the river basin model, important implications emerge from the results described above. Land and water scarcities impact on the production of crops, with the rainfed crop benefiting from increased scarcity *vis-à-vis* the irrigated crop. This raises policy implications with what to do about the massive past investment in irrigation in Australia and the protection and subsidies provided to the irrigated crops which have reduced necessary environmental riverflows. For an example (that reflects actual MDB circumstances that will be discussed in the next section), suppose small irrigation farmers downstream of a large private riverwater diversion storage in this regulated river basin are being denied benefit of the water in a severe drought situation which is destroying the riparian environment. Then, if the RBC buys back the large irrigator's water entitlements and retires them for the benefit of the ecosystem, the small downstream irrigation farmers still will be no better off.

The modelling conducted in this experiment indicates that water price 'taxation' in response to water scarcity helps ameliorate business cycle volatility as these 'taxes' rise over the long-term. This reduction in output, investment and profit volatility (hence lower risk premium) may actually benefit irrigation farmers, provided their long-term average return on capital remains equal to or above their new, lower, average opportunity cost of capital. Here is an example of tax-funded water sustainability measures being consistent with the continuing sustainable profitability of irrigated agriculture. This issue is reflected in the simulation exercise by the less severe troughs in recessions for the irrigated crop, which become more obvious as the general business cycles develop deeper troughs in the latter part of the century. These implications provide support for policy intervention due to systemic failure in the economic system as a result of ecological failures (Courvisanos, 2009).

The above two policy implications are only tentative, given the exploratory nature of this simplistic model that nonetheless captures some of the complex feedbacks and other interactions within and between the ecology and economy of a generic regulated river basin. It is the analytical implications which are far more important. These give the authors encouragement to pursue the current line of research further.

What the simulations reveal is that water and land scarcity stemming from ecological concerns about climate change (e.g., Garnaut, 2008) can be modelled in the context of the deterministic dynamic approach described in this paper. This produces a robust non-equilibrium integrated economic-ecological model which can produce scenarios with joint economic and ecosystem outcomes that are both positive. From the simulation exercise conducted, the incorporation of these economic modelling aspects with the dynamic non-equilibrium biophysical modelling of the MDB 'River Manager/River Operator' model, under the auspices of the eWater Cooperative Research Centre, appears to be highly compatible. Using a similar simulation time period, the River Manager framework carries out up to 70 model runs to generate results for each scenario over a 111 year modelling period. The River Manager model runs in a range of time steps from daily and weekly to monthly. Podger et al. (2008) describe the results from their project as providing the most accurate assessment, to date, of the available water resources in the MDB. They show how the impacts of climate change, farm dam development and groundwater development impact on local regions and throughout the MDB, as well as identifying the relevance of these impacts from both a local and basin-wide perspective.

Future Development of the Model with the Murray-Darling Basin

The aim of this economic modelling project is to test the ability of a fully specified regulated river basin simulation model to be viable and sustainable without collapsing into chaos over 100 years of historical time. With the preliminary success of the first version of the model as reported in this paper, the next step will be to improve it in future iterations leading up to incorporation of the real MDB ecosystem into the simulation, accompanied by real agricultural production data.

MDB ecosystem incorporation is the objective because the MDB is the most important agricultural region in Australia, consuming 70 per cent of all water used by agriculture whilst producing 40 per cent of the gross value of agricultural production. At the same time it is home to some of Australia's most treasured environmental resources. Nearly Australia's entire rice crop is grown in the Basin, by some 2,000 farming enterprises. Other major food crops are barley, oats, rye, buckwheat, triticale, and wheat; as well as horticultural crops including citrus, stone fruits, pome fruits, grapes and vegetables. The area under cotton production is about 93 per cent of the Australian total. In the long-term, the Basin has the potential to make a major contribution to the expansion of Australia's food exports, provided farming and grazing activities and practices are consistent with sustainable land management while remaining profitable. This requires an examination of whether each agricultural activity is undertaken and the extent to which this occurs. Drought conditions from 1998 until the floods of early 2010 have intensified this sustainability issue as output and incomes of many agricultural enterprises have come under extreme stress.

Since current approaches to the economic-ecological dilemma have been inadequate as noted earlier, serious problems like river salinity remain unresolved. Tensions pit specific regional interests along the whole MDB system against each other and continue not to be addressed.[7] A prime case in point concerns the world's largest cotton plantation on one of the largest private irrigation projects in the world - Cubbie Station, located in the north of the MDB on one of Queensland's rivers that feeds into the Darling and, ultimately, the Murray. Past investment in irrigation infrastructure and business enterprises creates the current dilemma about the use of the Cubbie water for reviving the fortunes of long-established irrigation farmers or instead reviving the ecosystem.[8]

The Murray-Darling Basin Authority (MDBA) is responsible for planning integrated management of the water resources of rivers in the MDB and

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[7] Goss (2003, p. 619) reports on the MDB that: "There is no agreed process for incorporating terrestrial biodiversity values at risk into a strategic response for dryland-salinity management. This is a public policy issue to be addressed." There is evidence that after 100 years, this public policy issue was finally being addressed by the COAG (Council of Australian Governments) Meeting of the 26 March 2008 agreeing to a new centralised water body and significant new Federal funding. However, as *The Australian* editorial on the following day states: "There is plenty of work yet to be done to decide what priority water projects will qualify for commonwealth funding and how best to deal with the thorny issue of buying back water rights that have been over-allocated by state governments" (27 March 2008, p. 17).

[8] The 93,000 hectares Cubbie Station has permits that allow the diversion and storage of more than 500,000 megalitres of water (enough to fill Sydney Harbour) which upsets downstream MDB users. Coming under financial pressure, Cubbie which is valued at $450m., went into voluntary administration on 30 October 2009. Queensland's Natural Resources Minister, Stephen Robertson, argued that the Federal Government should buy Cubbie and retire its water entitlements for the benefit of the environment, but the Federal Government refused (ABC News, 2009).

coordinates the distribution of water from the Murray River to regulatory bodies in New South Wales, Victoria and South Australia (MDBA, 2010). The MDBA is also a victim of the current trade-off approach to the economic-ecological dilemma when their draft plan resulted in civil unrest and draft plan burnings in many parts of the MDB.[9] This project's central objective is to provide the MDBA with a complexity-based economic-ecological computer model that allows for the operation in the MDB of a new eco-sustainable framework (Courvisanos, 2009) that iteratively resolves the dilemma described above.

The project plan is that all the nature-based and most of the technology-based equations in the model spreadsheet will be replaced in a future iteration with an existing ecologically-sophisticated biophysical model of Australia's MDB. Separately from this research project, initial hydrological work has been done on the Integrated Quantity and Quality Model (IQQM) for the MDB water catchments. This model is described in Simons et al. (1996) and Hameed and Podger (2001). IQQM carefully specifies MDB's topography, hydrology, microclimes, soil types, and other biophysical characteristics. Based on Welsh and Podger (2008), the IQQM has morphed into a larger River Manager/River Operator Model under the auspices of the eWater Cooperative Research Centre. This modelling project is connecting the various surface and groundwater models that describe the 18 sub-regions within the MDB region. In a complementary study, Young et al. (2008), note that the hydrological information utilised in the eWater CRC water modelling is only one of the important components of a broader assessment, one which must include the social, economic and environmental consequences of the expected changes in water availability. So it is to the lack of an economic component to specify the economic behaviour of actors in this region that the economic model described in this paper invites research attention.[10]

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[9] This occurred when the MDBA released its *Guide to the proposed basin plan* on October 11, 2010. In its effort to propose a return of significant environmental water flow back to the river basin, the authority raised the ire of the irrigation farmers who need this very water for the economic and social survival of their rural communities. For details, see the MDBA website at http://www.mdba.gov.au.

[10] As justification for the conduct of this project by the current authors and its planned incorporation into the River Manager model, in an email communication on 15 January 2010 to one of the authors, Dr. Peter Wallbrink (Executive Manager: River and Catchments, eWater CRC) stated: "Specifically regarding the economic impacts and economic change aspects, these have

The next iteration of the model will add more crops to the model, including a ‘crop of last resort’ (rainfed fodder) and also will feature more fine tuning to regularise the cycles. Further iterations of the model will add perennial crops and livestock, together with more fine tuning to regularise the cycles. Once a proof-of-concept model is successfully developed, a joint research project involving the Universities of Sydney and Ballarat, plus Imperial College London, will develop and test an integrated Economic and Ecological Sustainability Model for the Murray-Darling Basin. The focus of this collaboration will be on the interactions between agribusiness, changes in land use, energy usage, carbon emissions, and water consumption, given various climate change scenarios and government policy responses.

Conclusion

The simulation exercise conducted shows that it is possible to integrate a dynamic demand-based economic model with a supply-based two-crop river basin land-use ecological model. This provides confidence to proceed with the actual task of integrating a similar (but multi-commodity) non-equilibrium economic model with the already-specified and validated dynamic ecological MDB River Manager Model. A trial of the River Manager model was released to internal partners in mid-2009, with a full public release of the model due in September 2011.[11]

Testing out the first model iteration conveys an understanding of the nature and viability of the regulated river basin model, from both the model-building and political economy perspectives. The ability to unite a supply-based ecological model with a demand-based economic model provides strong encouragement for further research into this modelling approach that has ecological constraints incorporated into a dynamic non-equilibrium macroeconomic model equipped with multiple agricultural industries.

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fallen to the bottom of our action list…Realistically any functionally (sic) in these domains will be many years away.”

[11] Email communication on 15 January 2010 by Dr. Peter Wallbrink (Executive Manager: River and Catchments, eWater CRC).

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Appendix A: The River Basin Economy Model

Some key relationships in the computer model of the River Basin Economy are set out below. Note that 'pa' refers throughout to 'per annum'. All rice and wheat produced is exported, with virtually all inputs to production and commodities consumed being imported. The structural form of the model is a system of 158 equations and identities, comprising 47 for the rice sub-model, 45 for the wheat sub-model, and 66 for the macroeconomic section.

With the help of just 20 Greek letter parameters, these relationships mutually determine all quantities, prices and values, together with the realised rates of profit on capital (rrt % pa for rice and rw_t% pa for wheat).

Farmers have *static expectations*, i.e. they expect to realise rr_{t-1}% pa on capital devoted to rice and rw_{t-1}% pa on capital devoted to wheat. One or both sets of farmers may not realise their expectations at harvest/sale time in any given year, of course; this is what primarily drives the economy's dynamics.

The river basin's 'endowment' of arable land, suitable for raising either crop, is fixed at AE_t hectares. Potential irrigation water (Hip_t gigalitres pa for rice) and normal rainfall water (Hrn_t gigalitres pa for wheat) are also fixed in quantity.

Investment in Area Planted (hectares pa)
$Ar_t = Ar_{t-1}(1 + \varphi[rr_{t-1} - nr_t])$ for rice
$Aw_t = Aw_{t-1}(1 + \varphi[rw_{t-1} - nw_t])$ for wheat
If $Ar_t + Aw_t > AE_t$ the crop with the bigger expectation of profitability (r_{t-1}% pa) gets all the area it wants and the balance goes to the other crop. The two n_t% pa normal profit rates comprise the common interest rate plus a crop-specific risk premium. The term inside square brackets is the 'profitability gap' between expected return on capital and opportunity cost of capital. As this gap widens and narrows, so the river basin economy expands and contracts.

Investment in Land and Water(dollars pa)
$Ir_t = Ir_{t-1}(1 + \varphi[rr_{t-1} - nr_t])$ for rice

Investment in Land (dollars pa)

$Iw_t = Iw_{t-1}(1 + \varphi[rw_{t-1} - nw_t])$ for wheat

Wage Rate (dollars/worker pa)

$w_t = w_{t-1}(1 + \varepsilon[e_t - 1] + \rho\, gp_{t-1} + \gamma gq_t)$ and $w_t \geq w_{t-1}$ with $e_t = L_t/N_t$ being the labour utilisation ratio, gp_{t-1} last year's domestic inflation rate, and gq_t the growth rate of labour productivity. The inequality ensures that, unlike real wage rates, average money wage rates never fall (as in real-world advanced economies).

Crop Produced (tonnes pa)

$Q_t = A_{t-1}b_t$ for both crops, where crop yield (tonnes/hectare) is $b_t = b_{t-1}(1 + \beta gb_{t-1})$ without water constraints, but otherwise is reduced by the fractions Hir_t/Hip_t for rice and Hra_t/Hrn_t for wheat, where the numerators are irrigation water released and actual rainfall water, respectively. The variable gb_{t-1} is last year's growth rate of crop yield, which rises at the same rate as real crop yield investments (in constant dollars pa). These yield-raising investments comprise land improvements by the farmers themselves, plus government expenditures on research and agricultural extension by the River Basin Commission (RBC).

Realised Profit (dollars pa)

On each crop, this is Sales Revenue [Q_t times export price] minus the Variable Cost of wages, seed, fertiliser, fixed asset rentals, and RBC water and carbon charges.

Employment (workers pa)

$L_t = Q_t/q_t$ for both crops, where labour productivity (q_t tonnes/worker) grows at the fixed rate ($gq_t\%\, pa$). The economy's workforce (N_t workers pa) also grows at a fixed rate (gN_t % pa).

Appendix B: Graphical Representations of the Model Simulation Results

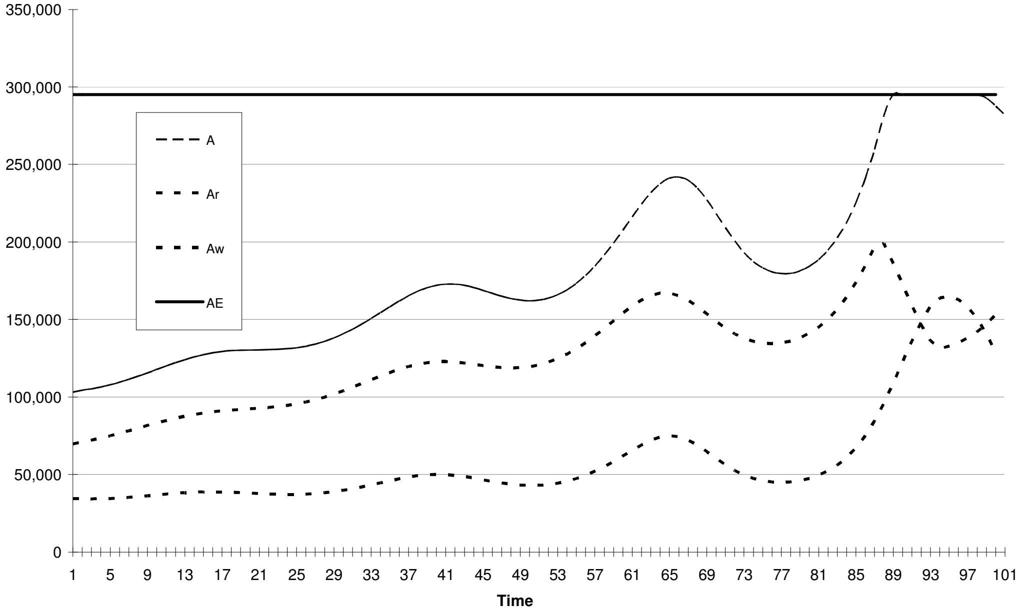

Figure 1: Area Planted (hectares)

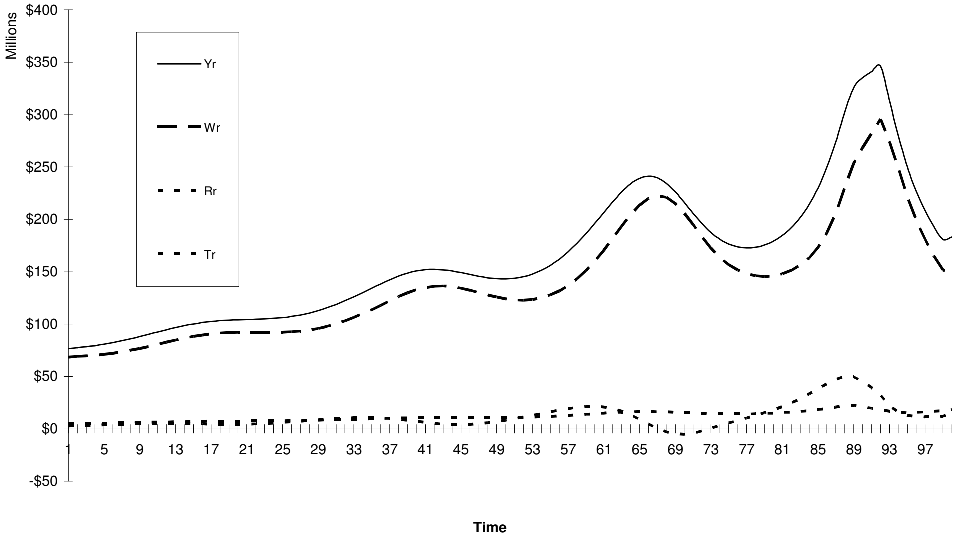

Figure 2: Real Gross Domestic Product and its Income Components

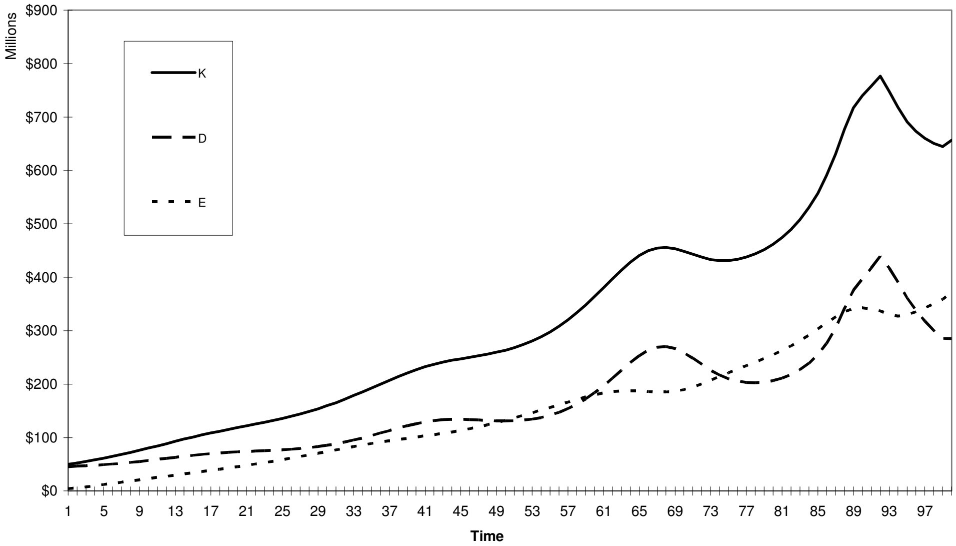

Figure 3: Assets, Debt and Equity

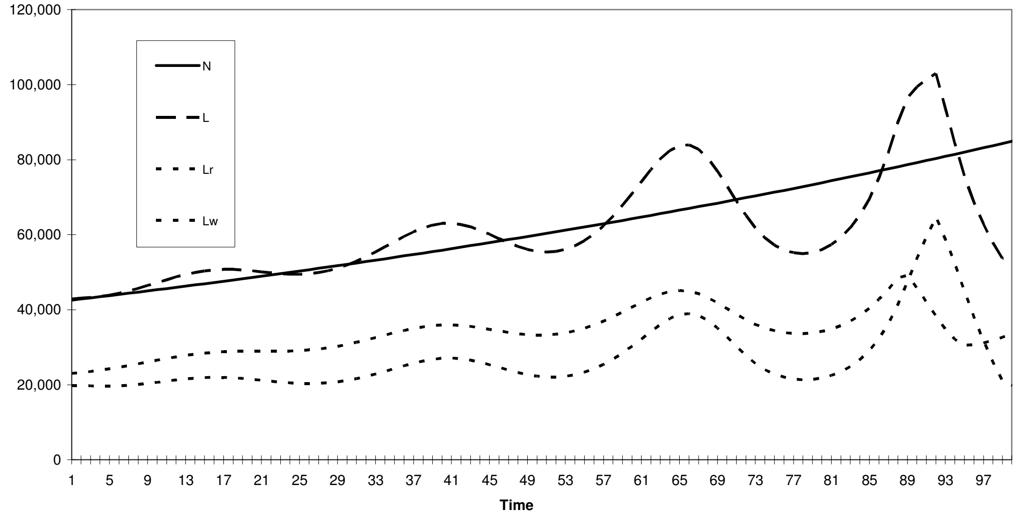

Figure 4: Labour Supply and Demand

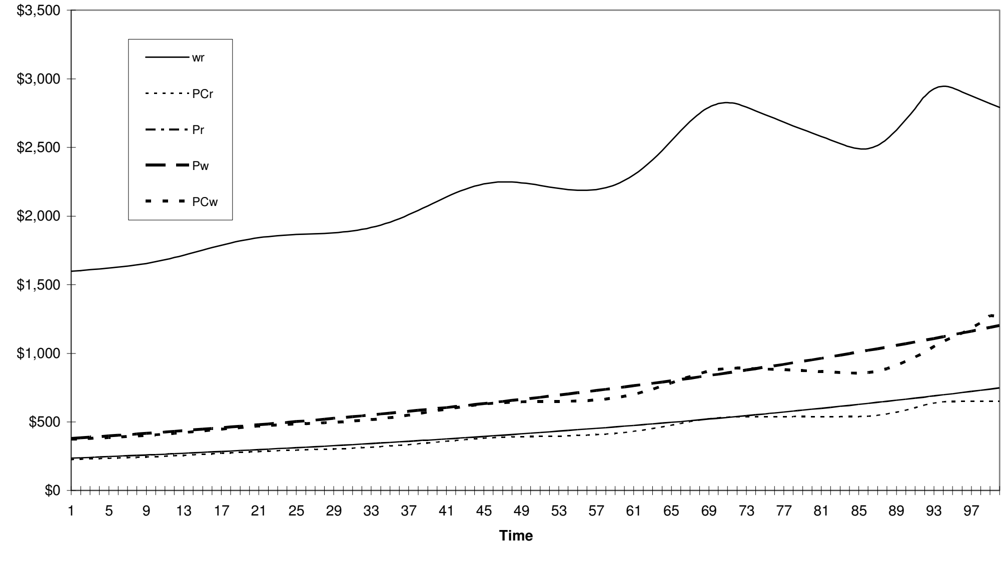

Figure 5: Real Wages, Prices and Prime Costs

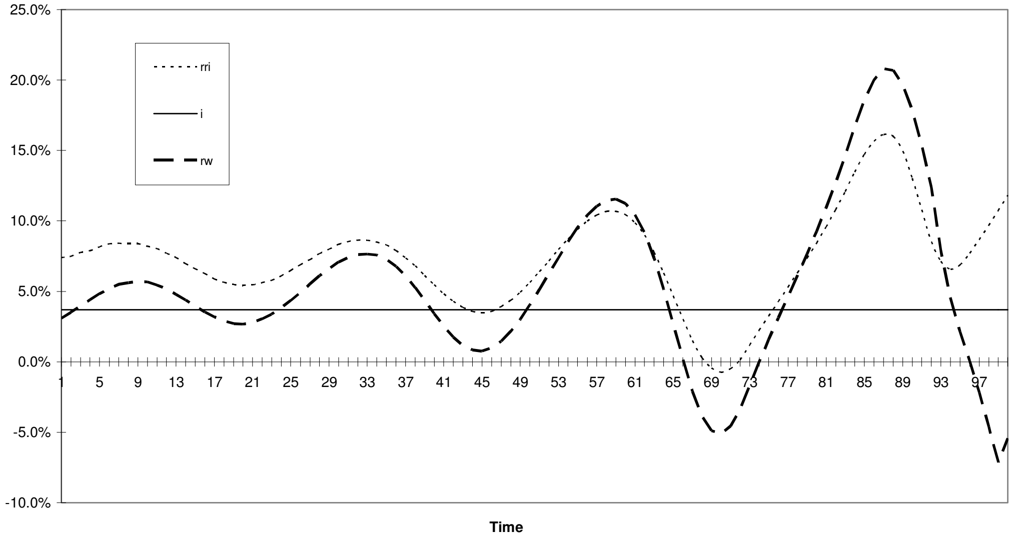

Figure 6: Interest and Profit Rates

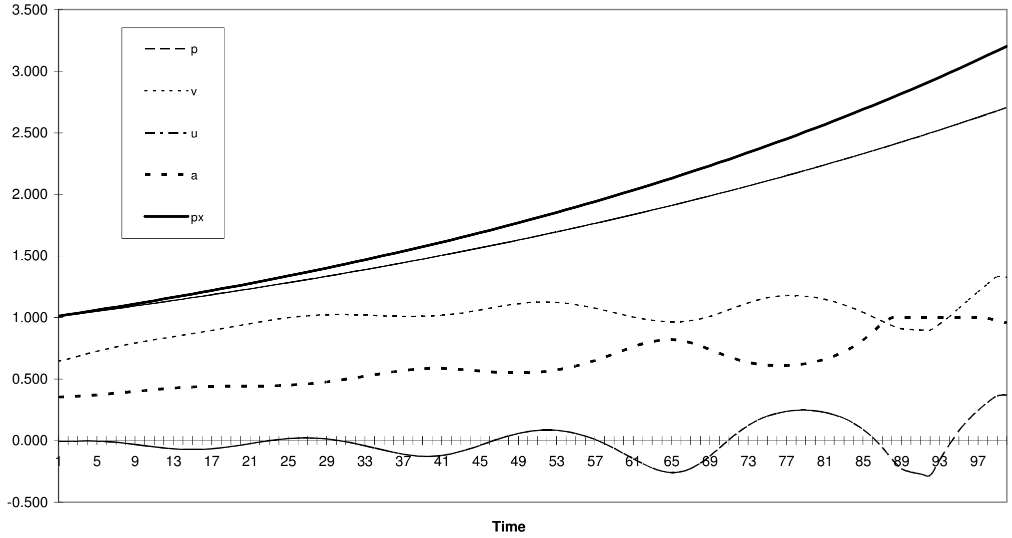

Figure 7: Various Ratios