

# A Post Keynesian Environmental Macroeconomic Model for Agricultural Water Sustainability under Climate Change in the Murray-Darling Basin, Australia

Ke Zhao, *PhD Candidate, RA, Sydney, RA, Ballarat* Colin Richardson, *Professor, Sydney,*  
Jerry Courvisanos, *Professor, Ballarat,* and John Crawford, *Professor, Sydney*

**Abstract**—Climate change has profound consequences for the agriculture of south-eastern Australia and its climate-induced water shortage in the Murray-Darling Basin. Post Keynesian Economics (PKE) macro-dynamics, along with Kaleckian investment and growth theory, are used to develop an ecological-economic system dynamics model of this complex nonlinear river basin system. The Murray-Darling Basin Simulation Model (MDB-SM) uses the principles of PKE to incorporate the fundamental uncertainty of economic behaviors of farmers regarding the investments they make and the climate change they face, particularly as regards water ecosystem services. MDB-SM provides a framework for macroeconomic policies, especially for long-term fiscal policy and for policy directed at the sustainability of agricultural water, as measured by socio-economic well-being considerations, which include sustainable consumption and investment in the river basin. The model can also reproduce other ecological and economic aspects and, for certain parameters and initial values, exhibit endogenous business cycles and ecological sustainability with realistic characteristics. Most importantly, MDB-SM provides a platform for the analysis of alternative economic policy scenarios. These results reveal the importance of understanding water ecosystem adaptation under climate change by integrating a PKE macroeconomic analytical framework with the system dynamics modelling approach. Once parameterised and supplied with historical initial values, MDB-SM should prove to be a practical tool to provide alternative long-term policy simulations of agricultural water and socio-economic well-being.

**Keywords**—Agricultural water, Macroeconomic dynamics, Modeling, Investment dynamics, Sustainability, Unemployment, Economics, Keynesian, Kaleckian.

## I. INTRODUCTION

**T**HIS paper introduces a modeling framework for Post Keynesian environmental macroeconomic dynamics that is motivated by recent attempts to formulate and study “integrated models” of the coupling between ecological and

K. Zhao is with the Faculty of Agriculture, Food and Natural Resources, and Center for International Security Studies, The University of Sydney, Sydney, New South Wales, and with the School of Business, University of Ballarat, Ballarat, Victoria, Australia e-mail: ke.zhao@sydney.edu.au.

C. Richardson is with the Center for International Security Studies, The University of Sydney, Sydney, New South Wales, Australia e-mail: colin.richardson@sydney.edu.au.

J. Courvisanos is with the School of Business, University of Ballarat, Ballarat, Victoria, Australia e-mail: j.courvisanos@ballarat.edu.au.

J. Crawford is with the Faculty of Agriculture, Food and Natural Resources, The University of Sydney, Sydney, New South Wales, Australia e-mail: john.crawford@sydney.edu.au.

Manuscript received October 20, 2011; revised November 15, 2011.

economic phenomena. These attempts stem from public concerns about several local and global issues, such as food security, water security, soil security, carbon emission, and global climate change. The challenge here is to describe the dynamic coupling between macroeconomic behavior and the functioning of the ecosystem over the very long term (around 100 years) in order to enhance local and global environmental management. In this context, Post Keynesian economists have already developed long-term growth models within the Kaleckian tradition, relying on the ideas that are rooted in Keynes’s economics.

For most economists, cost-benefit analysis, i.e. utility analysis in the long-run, is probably the principal panacea of most areas of policy analysis in environmental management. However, the assessment of the costs and benefits, especially in the environmental context of landscape, water usage and carbon emission, is often impossible not only in the long-run, but also in the short-run. This is due to lack of interface analysis between human and nature, uncertainty of ecosystem response and Keynesian fundamental uncertainty of individual human behavior for any policy and market expectations. Therefore integration into a system dynamics framework and consideration of features of the research objectives will frequently reinforce the usefulness of a social-ecological model and supply a predictable method in a complex non-equilibrium system.

Like popular system dynamics (SD) softwares, such as STELLA/iThink and Vensim, MATLAB Simulink also offers a stable programming environment for simulating the SD model applied for water sustainability assessment in the Murray-Darling Basin (MDB) of Australia. An important challenge faced by the MDB water sustainability authorities is to develop frameworks to simulate fundamental uncertain economic dynamics, rooted in the “animal spirits” of human beings, and highly uncertain water dynamics, such as unpredictable rainfall and water management tools and technology. This paper explores the use of the SD methodology toward this challenge.

After very briefly criticizing and reviewing relevant viewpoints on the existing modeling approaches of economic growth and presenting the framework for analysis in Section II, Section III describes the economic and ecological features of water and agricultural activities in the MDB ecosystem

and Australia. Section IV presents necessary components and assumptions of our SD model. Section V identifies the model parameters and presents the Murray-Darling Basin Simulation Model (MDB-SM), to apply to water investment behaviors, agricultural water usage and socio-economic well-being under macroeconomic policies targeting sustainable development. In section ?? we conclude the study and derive policy implications.

## II. THE ANALYTICAL FRAMEWORK

Neoclassical economists have developed approaches and results for managing natural resources management, solving local and global issues, and also completing many environmental-economic theories and treatments (ref. [1]–[10]). We will critically review these viewpoints that are based on the efficient market hypothesis (EMH), general equilibrium (GE), utility maximization, constant utility discount rate, and other consumption behavior assumptions.

The policy suggestions rooted in Neoclassical theory rely on the economy achieving GE in the long-run (for example, [11]) even though the theory is incapable of showing how that state is achieved via a series of short-run equilibria (or, more likely, disequilibria). Neoclassical macroeconomists also assert there is a “micro-foundation” of utility maximization deduced by humans’ self-interest. In addition, both New Classical and New Keynesian economists believe the market is a perfect medium for pricing environmental capitals even though they sometimes criticize each other ([12]–[15]). In contrast, our analytical framework roots in the respect of humans’ “animal spirits”, historical time and fundamental uncertainty and also in the reality of the environmental capital situation, social-economic consequences, capital-human coupling, etc..

### A. Brief Literature Review

Modern mainstream macroeconomics is dominated by the New Classical and New Keynesian Schools. Neither New Classical Economics nor New Keynesian Economics integrate well with environmental systems, or ecosystems ([16]–[18]), and they developed several economic growth theories separately ([13], [15], [19]–[22]). These approaches influence many economists and even ecological economists. When they criticize environmental economists at the macro-level, attacking wrong ecosystem service pricing is the principal viewpoint for ecological economists (ref. [23], [24]); nonetheless they still follow neoclassical frameworks, such as Solow’s growth model ([25]).

Post Keynesian economists, following to Keynes, have developed many fresh macroeconomic theories and policies, which has given rise to literatures on environmental issues from the mid-1990s. [26], for instance, published a Post Keynesian explanation on the Brundtland report “Our Common Future” ([27]), in which Vercelli concludes that “One of the main reasons for the deterioration of environmental problems may be ascribed precisely to the myopia of economic agents increasingly obsessed by very short-run objectives. Short-run rationality produces a profound irrationality in the longer run. Only a broader long-run rationality may produce a process

of sustainable development avoiding deep regrets.” Vercelli also argues that fundamental uncertainty in the market and policy expectation causes any optimization modeling based on rationality to fail. Furthermore [28] argues that one of the most distinguishing characteristics of the Post Keynesian theory of economic growth is the relationship between the growth of income and its distribution which, we believe, is also needed to coordinate environmental sustainable development and economic well-being in the long term.

### B. Framework for Analysis

Our study attempts to integrate an ecological-economic model based on a SD framework. The framework emphasizes feedback effects between agroecosystem and socio-economic system as well as involving macro-dynamic effects under aggregate investment behavior and socio-economic well-being. We will divide the framework into five units (ref. Equation (3) in Appendix) - (1) share of profit, (2) rate of capacity utilization, (3) potential labor productivity, (4) rate of employment, and (5) full employment labor-capital ratio - which model the behavior of each macroeconomic unit, once we focus on profit rate and add the environmental capitals into our system. Utilizing the profitability gap of Post Keynesian investment theory, we simulate the dynamic system (ref. Equation (5) in Appendix) and embed the dynamics into a sustainable long-run situation of economic well-being.

Macro-level behavior, introduced from traditional Keynesian “effective demand” theory ([29]) and developed by several Post Keynesian economists (e.g. [30]–[32]), is seen as an integration vehicle and is independent of micro-level behavior. Consumption behavior as a function of employment is more realistic than the assumption of full employment under perfect market conditions as in Classical and Neoclassical economic theory.

The Kaleckian model of growth, as developed by [33], has become quite important among Post Keynesian economists concerned with macroeconomics and effective demand issues ([34]). The model consists of three equations involving (1) income distribution, (2) saving and investment, and (3) the rate of capacity utilization. Our ecological-economic system simulation model is built on the Kaleckian model; through a Kaleckian investment dynamics equation involving environmental capital measures it will reflect the Keynesian economics and effective demand issues.

Fusion of uncertain climate change, water availability uncertainty, policy uncertainty (e.g. [35]–[37]) and human behavior “fundamental uncertainty” in the Kaleckian business cycles is likely to enhance environmental management over the long-run, and avoid inconsistency of short-term optimization with long-run environmental and economic risks.

## III. THE AGRICULTURAL WATER SYSTEM UNDER STUDY: MURRAY-DARLING BASIN IN AUSTRALIA

The Murray-Darling Basin (MDB) is the most important agricultural region in Australia; it consumes 70% of all of the Australian agricultural water and produces 40% of the gross value of agricultural production. The MDB covers over

one million square kilometers in five states and territories - Queensland, New South Wales, Australian Capital Territory, Victoria and South Australia (Figure 1). The MDB also is home to some of Australia's best environmental resources, such as seasonal water flow changes supporting a lot of plant and animal species, and wetlands feeding many fish and bird species. The MDB is under increasing tension between agricultural production and environmental protection and as such provides an ideal test bed for the empirical realization of a new sustainable development economic model, the Murray-Darling Basin Simulation Model (MDB-SM). In its economic-demographic aspects, MDB-SM will be an integrated ecological-economic model of supply-demand, complex systems, computer simulation, and economic well-being dynamics forecasting.

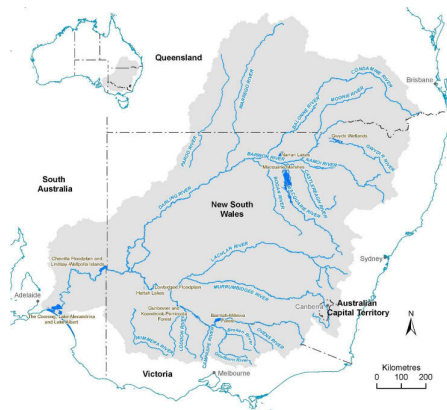


Fig. 1. Location of the Murray-Darling Basin, Australia, showing the capital cities and rivers

For convenience we list selected facts of the MDB here (Table I) as our complex system's index and initial values. We find from the basic natural properties that (1) total water consumption in the MDB is absolutely higher comparing with the area that the MDB occupies in Australia; (2) the conclusion is similar comparing with the population ratio in the MDB; and (3) both Gross Value of Agricultural Production (GVAP) and Gross Value of Irrigated Agricultural Production (GVIAP) are relatively lower than total water consumption. Therefore water security, even water crisis, in the MDB is a long-run challenge for Australian environmental management and sustainable development, and for Asia-Pacific area's food security.

As the Australian yearbook ( [39]) shows, in economic terms, the MDB provides \$187 billion in ecosystem services annually, and terrestrial ecosystems valued at up to \$325 billion per year. Biodiversity related industries also contribute significantly and directly to the Australian economy: it has been estimated that, per year, Australia's commercial fisheries are worth \$2.2 billion; kangaroo harvesting \$245 million; bush-food production \$100 million; and wildflower exports \$30 million.

With the expectation of global warming and increasing drought, the sustainable development of the Murray-Darling Basin is one of the most important environmental and resource

Items	Facts
Area of the MDB/Australia ( $km^2$ )	1,058,549/7,672,645
Agricultural Land in the MDB/Australia ( $km^2$ )	888,277/4,349,248
Irrigated Land Area ( $ha$ )	1,654,000
Non-irrigated Land Area ( $ha$ )	87,174,000
Quantity of Irrigated Farms <sup>1</sup>	16,600
Quantity of Non-irrigated Farms <sup>2</sup>	37,300
Annual Rainfall in the MDB <sup>3</sup> ( $GL$ )	530,618
Annual Run-off in the MDB <sup>4</sup> ( $GL$ )	23,609
Total Water Consumption in the MDB/Australia ( $GL$ )	7,720/11,689
Total Population in the MDB/Australia	2,004,560/19,855,290
Total Labor Force in the MDB/Australia	1,583,390/15,879,920
Unemployment Rate in the MDB/Australia (%)	5.0/5.2
Gross Value of Agricultural Production (GVAP) in the MDB/Australia (\$m)	14,991/38,541
Gross Value of Irrigated Agricultural Production (GVIAP) in the MDB/Australia (\$m)	4,576/10,486

TABLE I

SOME FACTS OF THE MDB BASED ON 2005-2006 DATA, SOURCE: [38]

policy challenges at present.

[40] developed for the MDB Authority unveils the ecological-economic features of the MDB from six aspects, that is, population; water for homes; water for industry; selected industry profiles including agriculture, mining, manufacturing, construction, irrigated agriculture and tourism; economic wellbeing; and community wellbeing - to guide further policy decision making.

Another important document ( [36]) expects that "... the impacts of climate change by 2030 are uncertain; however, surface water availability across the entire MDB is more likely to decline than to increase. A decline in the south of the MDB is more likely than in the north. In the south of the MDB, a very substantial decline is possible. In the north of the MDB, significant increases are possible. The median decline for the entire MDB is 11 percent - 9 percent in the north of the MDB and 13 percent in the south of the MDB." and releases a project for long-term water availability in the MDB under a number of climate change scenarios.

As an important agricultural area in Australia, the MDB has some detailed historical records, especially after 1994. However with different long term observation and prediction purposes, we will start with different data. Therefore we substitute the MDB macroeconomic systems data by Australian data and believe this is safe and reliable for illustrative purposes.

First of all, rainfall is the main driver of variability in the hydrological cycle under a scenario of climate change. Average rainfall decreases in the most recent ten years may indicate that the stronger expectations for drought by farmers, consumers and policy-makers are more likely over the long term. The expectation will influence investment behavior, consumption behavior and policies which is difficult to solve using the Neoclassical theories that have dominated Australian drought policies since the 1980's (e.g. [41]). Rainfall in the MDB has experienced big fluctuations in the last 100 years (Figure 2).

As an important environmental services input for agricul-

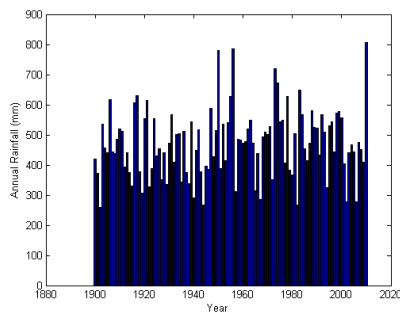


Fig. 2. Annual rainfall in the MDB, Australia (1900-2010)

tural production, in history, rainfall has already had serious impacts on the farmers' profit expectation and furthermore their investment behavior, and then the unemployment rate (Figure 3). Three recent most serious droughts in Australia correlate with the unemployment rate, especially the unemployment rate hitting nearly 11% in 1994 when 1994-1995 drought happened. We may not argue that droughts are the principal factor causing the unemployment, however unstable water management and poor environmental resilience deteriorate economic well-being, especially when economic depression occurred.

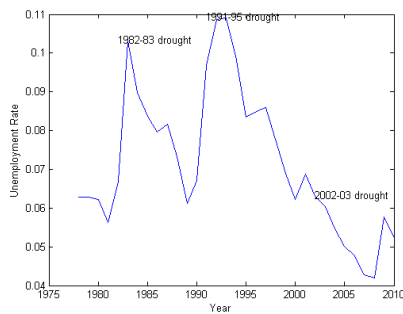


Fig. 3. The relationship between unemployment rate and drought in Australia (1980-2010)

Also the GVAP depends on annual rainfall seriously. Figure 4 shows the relation between historical droughts and GVAP, with GVAP having local minimum points at the time periods when droughts happen.

Secondly, we measure water productivity in physical term  $ML/ha$  (Table II) in the irrigated agricultural land, and find that rice is the most water-consumptive cereal, uses over 5 times more water than other cereals, and 2.6 times more than the average application rate, that is,  $4.7 ML/ha$ .

Thirdly, we introduce land productivity in economic term in  $\$/ha$  and water productivity  $\$/ML$  (Table III) to measure the economic returns of these two most important environmental capitals in irrigated agricultural production, and find that vegetables is the most highly-efficient commodity in land and water uses while fruit (excluding grapes) is in second position.

Australia has seen a rapid population growth in the past 100 years (Figure 5) and also has a population project for the

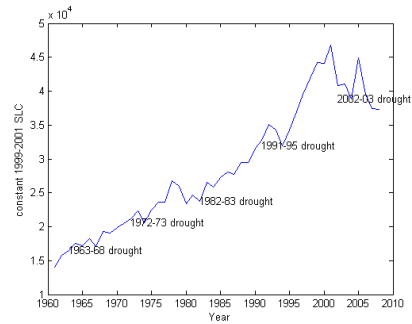


Fig. 4. The relationship between GVAP and drought in Australia (1960-2010)

	Volume (GL)	Area (,000 ha)	Application Rates (ML/ha)
Pasture	2,571	717	3.5
Rice	1,252	102	12.3
Cereals (excl. rice)	782	329	2.4
Cotton	1,574	247	6.4
Grapes	515	106	4.9
Fruit (excl. grapes)	413	75	5.5
Vegetables	152	32	4.7
Other agriculture	461	46	10.0
Total	7720	1654	4.7

TABLE II  
IRRIGATED AREA, WATER CONSUMPTION AND IRRIGATED APPLICATION RATES BY SELECTED AGRICULTURAL COMMODITY IN THE MDB 2005-06, SOURCE: [38] TABLE 3.2 AND 3.3

future century (Figure 6) published by [42] and [43].

#### IV. MAIN COMPONENTS AND ASSUMPTIONS

The model of macroeconomic system integrates five units - share of profit, rate of capacity utilization, potential labor productivity, rate of employment and full employment labor-capital ratio - which are discussed in detail below. The full system of equations of our ecological-economic model is presented in A and model variables to solve for endogenously are defined in Table IV. We introduce the macro-micro model below by simple Kaleckian tradition.

	GVIAP (\$m)	Return in Land (\$t/ha)	Return in Water (\$t/ML)
Pasture	1,070	1.5	0.4
Rice	274	2.7	0.2
Cereals (excl. rice)	92	0.3	0.1
Cotton	797	3.2	0.5
Grapes	722	6.8	1.4
Fruit (excl. grapes)	898	12.0	2.2
Vegetables	530	16.6	3.5
Other agriculture	193	4.2	0.4

TABLE III  
IRRIGATED AREA, WATER CONSUMPTION AND IRRIGATED APPLICATION RATES BY AGRICULTURAL COMMODITY IN THE MDB 2005-06, SOURCE: [38] TABLES 3.2, 3.3 AND 4.23

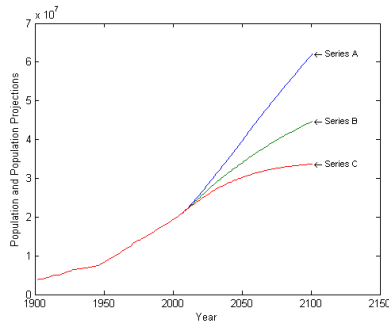


Fig. 5. Population and population projections in Australia (1900-2100)

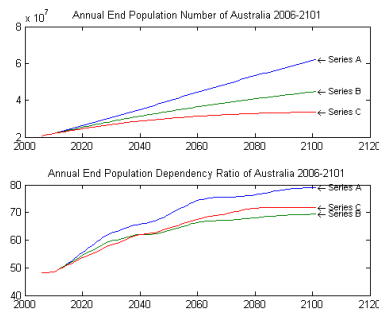


Fig. 6. Population and dependency ratio in Australia (2006-2100)

A. Share of profit

We simply employ Kalecki’s assumption that capitalists earn what they spend while workers spend what they earn, that is, capitalists earn profits according to the amount of money they spend on capital goods and workers spend the wages of their labor on consumption goods. Given the definition of aggregate output in Equation (2), we simplify the output equation to

$$\nu + \Pi = 1 \tag{1}$$

In fact this is also the income distribution equation.

B. Rate of capacity utilization

For Neoclassical economists who believe in the efficient market, the market will clear automatically, therefore the rate of capacity utilization will become 1 when general equilibrium eventually is reached. However more and more economists now recognize general equilibrium (capacity utilization rate is 1) is just one specific condition in Keynesian economics; more usually, the market is dynamic with respect to capacity utilization, due to the fluctuation of effective demand, comprising consumption and investment outlays.

We exogenously describe the rate of capacity utilization as a ratio of output to potential output, with the latter variable depending on the current technology, environmental capitals, economic capitals, and full employment. We will assume a constant growth of the rate.

Variable	Definition	Units
$Y$	Output	Dollars
$I$	Investment	Dollars
$W$	Wage-unit	Dollars
$L$	Employment	Workers
$R$	Profit	Dollars
$\nu = WL/Y$	Share of wages	Percentage
$\Pi = R/Y$	Share of profit	Percentage
$K$	Capital	Dollars
$Y^P$	Potential output	Dollars
$L^S$	Workforce	Workers
$u = Y/Y^P$	Realized rate of capacity utilization	Percentage
$y^P = Y^P/L$	Potential labor productivity	Percentage
$v = K/Y^P$	Capital to capacity ratio	Percentage
$e = L/L^S$	Rate of employment	Percentage
$l^S = L^S/K$	Full employment labor-capital ratio	Percentage
$r$	Profit rate	Percentage
$s_p$	Propensity to save	Percentage
$\gamma$	Trend rate of growth of sales	Percentage
$g$	Profitability gap	Percentage
$Z$	Aggregate supply price	Dollars
$D$	Expected return/Effective demand	Dollars
$\phi : Z = \phi(L)$	Aggregate supply function	Function
$f : D = f(L)$	Effective demand function	Function
$D_1$	Consumption demand	Dollars
$D_2$	Investment demand	Dollars
$\chi : D_1 = \chi(L)$	Aggregate consumption function	Function
$E = WL$	Wages (and Salaries) bill	Dollars

TABLE IV  
DEFINITIONS OF MODEL VARIABLES

C. Potential labor productivity

When full employment happens we measure the condition by potential labor productivity, meaning every workers will contribute the output, earn the wage and have the means to do consumption, namely, have a positive propensity to consume. We can benefit from the variable, potential labor productivity, to connect with effective demand in the whole macroeconomic system, which is a most important index indicating the system’s sustainability. This is not only in the Keynesian tradition but is one of our innovations to treat the feedback of the system.

D. Employment rate

One of the purposes of our analysis is the derivation of a sustainable effective demand time-path and the evaluation of employment guarantee and ecosystem protection policies for achieving potential full employment, economic well-being and sustainable development. The employment rate as an important economic indicator can describe not only the waste of labor’s productivity but also the perspective of economic activity and potential environmental wastes.

E. Labor-capital ratio under full employment

In the light of [29] full employment is a special situation that is associated with sufficiently high effective demand. Therefore, full employment is an effect of effective demand rather than being a cause of it. We introduce the ratio of labor to capital under full employment as a measure of technology

and effective demand in order to coordinate economic well-being, technological progress and the current environmental capital stocks.

*F. Profitability gap and investment equation*

[44] examines four investment theory approaches on fixed assets: Classical “uniform profitability” investment theory, Keynes’s “marginal efficiency” investment theory, Kalecki’s accelerator investment functions, and Neoclassical *q*-ratio investment theory. They show that all these theories involve a common profitability gap, either implicitly or explicitly. This outstanding finding bridges investment behavior and the macroeconomic system in a unified investment-oriented scheme and erases the differences between Classical, New Classical, Neoclassical, Keynesian, New Keynesian, and Post Keynesian Schools on investment theories.

Investment equation (4) means that the current investment margin is an accelerator of previous investment, that is, based on the previous investment and a much broader profitability gap, there is a larger acceleration which involves humans’ “animal spirits”.

*G. Saving equation*

Saving function (6) comes from the typical Cambridge saving equation, which is given by the product of two terms - the propensity to save out of profits and the profit rate. Considering a gap between aggregate saving and aggregate investment, the saving function, in fact, indicates the growth rate of the capital stock.

V. SIMULATION RESULTS

We select some important results of the Murray-Darling Basin Simulation Model. From the results, we can find that (1) both income and profitability gap in the non-irrigation farms receive more influences by rainfall than in the irrigation farms; (2) both investment and land use behave with a similar tendency.

Income in Irrigation Agriculture (Figure 7)

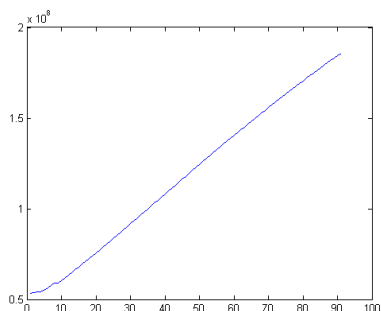


Fig. 7. Income in Irrigation Agriculture

Income in Non-irrigation Agriculture (Figure 8)  
 Investment in Irrigation Agriculture (Figure 9)  
 Investment in Non-irrigation Agriculture (Figure 10)

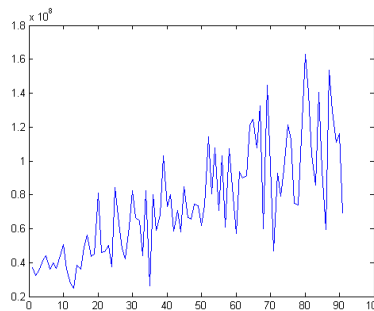


Fig. 8. Income in Non-irrigation Agriculture

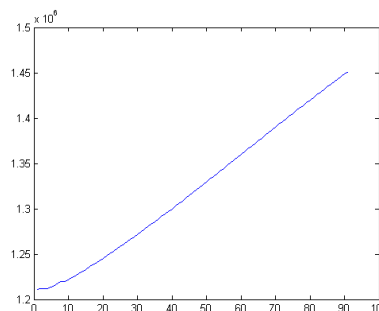


Fig. 9. Investment in Irrigation Agriculture

Land in Irrigation Agriculture (Figure 11)  
 Land in Non-irrigation Agriculture (Figure 12)  
 Profitability Gap in Irrigation Agriculture (Figure 13)  
 Profitability Gap in Non-irrigation Agriculture (Figure 14)

VI. CONCLUSION

That local issues should be dealt with locally and global ones globally is obvious, but what a less obvious is to understand the sustainability of ecosystem and the development of economics. The complexity and dynamics in the coupling of ecological and economic systems complicates the problem analysis, therefore no panacea exists (ref. [24], [45]–[47]). The capital stocks, natural environmental situation, current labor-capital ratio, distribution of profit, and environmental stability and resilience are keys for policy-making.

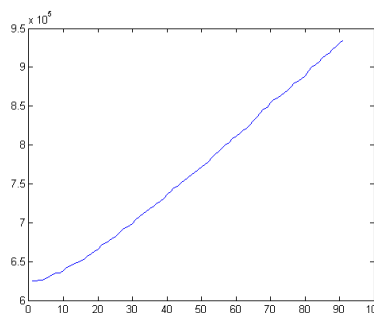


Fig. 10. Investment in Non-irrigation Agriculture

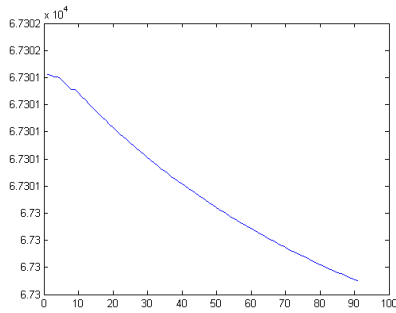


Fig. 11. Land in Irrigation Agriculture

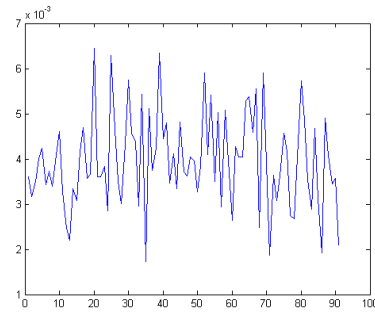


Fig. 14. Profitability Gap in Non-irrigation Agriculture

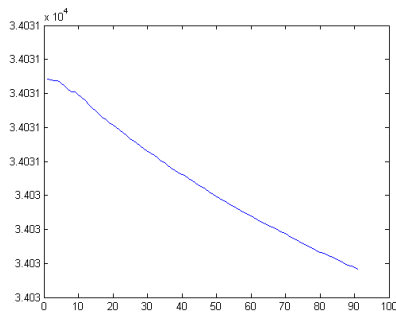


Fig. 12. Land in Non-irrigation Agriculture

We argue here that the balance of wages and profit is the key, in order to avoid over-investment in the environmental capital and over-consuming the ecosystem services.

Finally, Post Keynesian economics, rooted in recognition of the economic macro-dynamics theory and complexity of the ecosystem, suggests how to practise sustainable development policy-making in the long-run, so here too we see some features of the ecological-economic complex system.

APPENDIX A  
THE SYSTEM OF EQUATIONS

A. Macroeconomic Module

Output in income approach

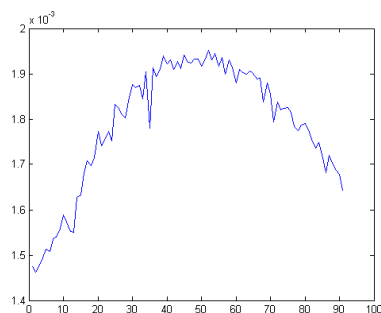


Fig. 13. Profitability Gap in Irrigation Agriculture

$$Y = WL + R \tag{2}$$

Profitability equation

$$r = \frac{R}{K} = \frac{R}{Y} \frac{Y}{Y^P} \frac{Y^P}{L} \frac{L}{L^S} \frac{L^S}{K} = \Pi u y^P e l^S \tag{3}$$

B. Investment Module (Source: [44])

Investment equation

$$\frac{dI(t)}{dt} = g(t)I(t) \tag{4}$$

Profitability gap

$$\frac{dr(t)}{dt} = g(t) \tag{5}$$

Saving function

$$g^s = s_p r, s_p > 0 \tag{6}$$

APPENDIX B

MURRAY-DARLING BASIN SIMULATION MODEL

A. Non-irrigation Agriculture

Non-irrigation Agricultural Production

$$\text{Production} = \text{Land Area} \times \text{Yield} \tag{7}$$

Non-irrigation Yield

$$\text{Yield} = \alpha_{\text{Rainfall}} \times \text{Rainfall} \tag{8}$$

Price of Non-irrigation Agricultural Production

$$\frac{d}{dt} \text{Non-irrigation Price} = r_{\text{Price}} \times \text{Non-irrigation Price} \tag{9}$$

Non-irrigation Agricultural Income

$$\text{Income} = \text{Production} \times \text{Non-irrigation Price} \tag{10}$$

Price of Land

$$\frac{d}{dt} \text{Land Price} = r_{\text{Land Price}} \times \text{Land Price} \tag{11}$$

Non-irrigation Agricultural Capital Stocks



## C. Market

$$\text{Capital} = \text{Income} \times \text{Turnover} + \text{Land} \times \text{Land Price} \quad (12)$$

Non-irrigation Agricultural Profit

$$\text{Profit} = \text{Income} - \text{Wage Bills} \quad (13)$$

Profitability

$$\text{Profitability} = \frac{\text{Profit}}{\text{Capital}} \quad (14)$$

## B. Irrigation Agriculture

Irrigation Agricultural Production

$$\text{Production} = \text{Land Area} \times \text{Yield} \quad (15)$$

Irrigation Yield

$$\frac{d}{dt} \text{Yield} = r_{\text{Yield}} \times \text{Yield} \quad (16)$$

Price of Irrigation Agricultural Production

$$\frac{d}{dt} \text{Irrigation Price} = r_{\text{Price}} \times \text{Irrigation Price} \quad (17)$$

Irrigation Agricultural Income

$$\text{Income} = \text{Production} \times \text{Irrigation Price} \quad (18)$$

Price of Land

$$\frac{d}{dt} \text{Land Price} = r_{\text{Land Price}} \times \text{Land Price} \quad (19)$$

Irrigation Agricultural Capital Stocks

$$\text{Capital} = \text{Income} \times \text{Turnover} + \text{Land} \times \text{Land Price} \quad (20)$$

Water Price

$$\frac{d}{dt} \text{Water Price} = r_{\text{Water Price}} + \frac{d}{dt} \text{Rainfall} \quad (21)$$

Water Efficiency

$$\frac{d}{dt} \text{Water Efficiency} = r_{\text{Water Efficiency}} \times \text{Water Efficiency} \quad (22)$$

Water Usage

$$\text{Water Usage} = \text{Land} \times \text{Water Efficiency} \quad (23)$$

Water Bills

$$\text{Water Bills} = \text{Water Price} \times \text{Water Usage} \quad (24)$$

Irrigation Agricultural Profit

$$\text{Profit} = \text{Income} - \text{Wage Bills} - \text{Water Bills} \quad (25)$$

Profitability

$$\text{Profitability} = \frac{\text{Profit}}{\text{Capital}} \quad (26)$$

Labor Supply

$$\text{Labor Supply} = \frac{\text{Population}}{1 + \text{Dependency Ratio}} \quad (27)$$

Labor

$$\text{Labor} = \min(\text{Labor Supply}, \frac{\text{Capital}}{\text{Capital-Labor Ratio}}) \quad (28)$$

Wage-unit

$$\frac{d}{dt} \text{Wage-unit} = r_{\text{Wage-unit}} \times \text{Wage-unit} \quad (29)$$

Wage Bills

$$\text{Wage Bills} = \text{Labor} \times \text{Wage-unit} \quad (30)$$

Producer Price Index

$$\frac{d}{dt} \text{Producer Price} = r_{\text{Producer Price}} \times \text{Producer Price} \quad (31)$$

Capital

$$\frac{d}{dt} \text{Capital} = \frac{\text{Investment}}{\text{Producer Price}} \quad (32)$$

Total Capital Stocks

$$\text{Total Capital Stocks} = \text{Income} \times \text{Turnover} + \text{Capital} \quad (33)$$

Profit

$$\text{Profit} = \text{Income} - \text{Wage Bills} - \text{Capital Depreciation} \quad (34)$$

Profitability

$$\text{Profitability} = \frac{\text{Profit}}{\text{Capital}} \quad (35)$$

## REFERENCES

- [1] H. Hotelling, "The economics of exhaustible resources," *The Journal of Political Economy*, vol. 39, no. 2, pp. 137–175, 1931.
- [2] K. J. Arrow, "The economic implications of learning by doing," *The Review of Economic Studies*, vol. 29, no. 3, pp. 155–173, 1962.
- [3] K. J. Arrow and A. C. Fisher, "Environmental preservation, uncertainty, and irreversibility," *The Quarterly Journal of Economics*, vol. 88, no. 2, pp. 312–319, 1974.
- [4] P. Dasgupta and G. Heal, "The optimal depletion of exhaustible resources," *The Review of Economic Studies*, vol. 41, pp. 3–28, 1974.
- [5] K. Arrow, P. Dasgupta, and K.-G. Mler, "Evaluating projects and assessing sustainable development in imperfect economies," *Environmental and Resource Economics*, vol. 26, no. 4, pp. 647–685, 2003.
- [6] K. Arrow, P. Dasgupta, L. Goulder, G. Daily, P. Ehrlich, G. Heal, S. Levin, K. G. Maler, S. Schneider, D. Starrett, and B. Walker, "Are we consuming too much?" *Journal of Economic Perspectives*, vol. 18, no. 3, pp. 147–172, 2004.
- [7] K. J. Arrow, G. Daily, P. Dasgupta, P. Ehrlich, L. Goulder, G. Heal, S. Levin, K. G. Maler, S. Schneider, D. Starrett, and B. Walker, "Consumption, investment, and future well-being: Reply to daly et al," *Conservation Biology*, vol. 21, no. 5, pp. 1363–1365, 2007.
- [8] K. G. Maler, "Sustainable development and resilience in ecosystems," *Environmental & Resource Economics*, vol. 39, no. 1, pp. 17–24, 2008.
- [9] K. G. Maler, S. Aniyar, and A. Jansson, "Accounting for ecosystems," *Environmental & Resource Economics*, vol. 42, no. 1, pp. 39–51, 2009.



- [10] B. Walker, L. Pearson, M. Harris, K. G. Maler, C. Z. Li, R. Biggs, and T. Baynes, "Incorporating resilience in the assessment of inclusive wealth: An example from south east australia," *Environmental & Resource Economics*, vol. 45, no. 2, pp. 183–202, 2010.
- [11] S. Hallegatte, M. Ghil, P. Dumas, and J. C. Hourcade, "Business cycles, bifurcations and chaos in a neo-classical model with investment dynamics," *Journal of Economic Behavior & Organization*, vol. 67, no. 1, pp. 57–77, 2008.
- [12] J. Lucas, R. E. and T. J. Sargent, "After keynesian macroeconomics," *Quarterly Review*, no. Spr, 1979.
- [13] R. J. Barro, "New classicals and keynesians, or the good guys and the bad guys," National Bureau of Economic Research, Inc, Tech. Rep., May 1989.
- [14] N. G. Mankiw, "The reincarnation of keynesian economics," *European Economic Review*, vol. 36, no. 2-3, pp. 559–565, 1992.
- [15] N. G. Mankiw, D. Romer, and D. N. Weil, "A contribution to the empirics of economic growth," *The Quarterly Journal of Economics*, vol. 107, no. 2, pp. 407–437, 1992.
- [16] H. E. Daly, "Towards an environmental macroeconomics," *Land Economics*, vol. 67, no. 2, pp. 255–259, 1991.
- [17] P. A. Lawn, "On heyec's proposal to establish an environmental macroeconomics," *Environment and Development Economics*, vol. 8, no. 01, pp. 31–56, 2003.
- [18] C. Carraro, R. Gerlagh, and B. v. d. Zwaan, "Endogenous technical change in environmental macroeconomics," *Resource and Energy Economics*, vol. 25, no. 1, pp. 1–10, 2003.
- [19] R. M. Solow, "A contribution to the theory of economic growth," *The Quarterly Journal of Economics*, vol. 70, no. 1, pp. 65–94, 1956.
- [20] —, "Technical change and the aggregate production function," *The Review of Economics and Statistics*, vol. 39, no. 3, pp. 312–320, 1957.
- [21] —, "The economics of resources or the resources of economics," *American Economic Review*, vol. 64, no. 2, pp. 1–14, 1974.
- [22] K. Arrow, B. Bolin, R. Costanza, P. Dasgupta, C. Folke, C. S. Holling, B.-O. Jansson, S. Levin, K.-G. Mler, C. Perrings, and D. Pimentel, "Economic growth, carrying capacity, and the environment," *Ecological Economics*, vol. 15, no. 2, pp. 91–95, 1995.
- [23] D. I. Stern, "Limits to substitution and irreversibility in production and consumption: A neoclassical interpretation of ecological economics," *Ecological Economics*, vol. 21, no. 3, pp. 197–215, 1997.
- [24] R. Meinzen-Dick, "Beyond panaceas in water institutions," *Proceedings of the National Academy of Sciences of the United States of America*, vol. 104, no. 39, pp. 15 200–15 205, 2007.
- [25] R. U. Ayres, "Sustainability economics: Where do we stand?" *Ecological Economics*, vol. 67, no. 2, pp. 281–310, 2008.
- [26] A. Vercelli, *Sustainable development, rationality, and time*. Dordrecht: Kluwer Academic Publishers, 1998, p. 259276.
- [27] G. H. Brundtland, *Our common future, Report of the World Council For Economic Development*. New York: Oxford University Press, 1987.
- [28] L. L. Pasinetti, "The cambridge school of keynesian economics," *Cambridge Journal of Economics*, vol. 29, no. 6, pp. 837–848, 2005.
- [29] J. M. Keynes, *The General Theory of Employment, Interest and Money*. London: Palgrave Macmillan, 1936.
- [30] M. Kalecki, "Trend and business cycles reconsidered," *Economic Journal*, vol. 78, no. 310, pp. 263–276, 1968.
- [31] M. Lavoie, *Introduction to Post-Keynesian Economics, 2nd edition*, 2nd ed. Basingstoke: Palgrave Macmillan, 2009.
- [32] M. Setterfield, Ed., *Handbook of Alternative Theories of Economic Growth*. Cheltenham, UK, Northampton, MA, USA: Edward Elgar Pub, 2010.
- [33] A. K. Dutt, "Stagnation, income distribution and monopoly power," *Cambridge Journal of Economics*, vol. 8, no. 1, pp. 25–40, 1984.
- [34] E. Hein, M. Lavoie, and T. van Treeck, "Some instability puzzles in kaleckian models of growth and distribution: a critical survey," *Cambridge Journal of Economics*, vol. 35, no. 3, pp. 587–612, 2011.
- [35] D. Adamson, T. Mallawaarachchi, and J. Quiggin, "Water use and salinity in the murray-darling basin: A state-contingent model," *Australian Journal of Agricultural & Resource Economics*, vol. 51, no. 3, pp. 263–281, 2007.
- [36] CSIRO, "Water availability in the murray-darling basin: A report to the australian government from the csiro murray-darling basin sustainable yields project," CSIRO, Tech. Rep., 2008, @Zhao.
- [37] D. Adamson, T. Mallawaarachchi, and J. Quiggin, "Declining inflows and more frequent droughts in the murraydarling basin: climate change, impacts and adaptation," *Australian Journal of Agricultural & Resource Economics*, vol. 53, no. 3, pp. 345–366, 2009.
- [38] Australian Bureau of Statistics, "Water and the murray-darling basin - a statistical profile, 2000-01 to 2005-06," 2008.
- [39] —, "Year book australia 2009-10," Tech. Rep., 2010.
- [40] ABS/ABARE/BRS, "Socio-economic context for the murray-darling basin," Murray-Darling Basin Authority, Tech. Rep., 2009.
- [41] L. C. Botterill, "Uncertain climate: The recent history of drought policy in australia," *Australian Journal of Politics and History*, vol. 49, no. 1, pp. 61–74, 2003.
- [42] Australian Bureau of Statistics, "Australian historical population statistics, 2008," 2008.
- [43] —, "Population projections, australia, 2006 to 2101," 2008.
- [44] C. Richardson and P. Romilly, "Investment functions and the profitability gap," *Journal of Post Keynesian Economics*, vol. 31, no. 1, pp. 35–56, 2008.
- [45] E. Ostrom, M. A. Janssen, and J. M. Anderies, "Going beyond panaceas," *Proceedings of the National Academy of Sciences of the United States of America*, vol. 104, no. 39, pp. 15 176–15 178, 2007.
- [46] E. Ostrom, "A diagnostic approach for going beyond panaceas," *Proceedings of the National Academy of Sciences of the United States of America*, vol. 104, no. 39, pp. 15 181–15 187, 2007.
- [47] W. A. Brock and S. R. Carpenter, "Panaceas and diversification of environmental policy," *Proceedings of the National Academy of Sciences of the United States of America*, vol. 104, no. 39, pp. 15 206–15 211, 2007.