Winter 2024, PPHA 39930
Instructor: Amir Jina
Individual assignment 3
Due: 14th February, 2024

Directions: Please submit a PDF write-up with your answers to questions.

I. Adaptation policy analysis

First, read the following description of the case study. Most aspects of the case study are real, though we will use a little artistic license at times. You are working for the Department of Water Resources in the Indian state of Punjab. Punjab lies in north-western India, near the border with Pakistan. Since the Green Revolution, it has become one of India's most important agricultural areas and agriculture is the biggest sector of the state's economy, although there is a growing manufacturing and service sector, based in the state's main towns such as Ludhiana and Amritsar. Between 2008 and 2018, the state's population grew by around 10% (having grown by around 15% in the previous decade). At the same time, state GDP increased by a factor of around 2.5. Punjab has a level of income *per capita* that is higher than average by Indian standards, but much lower than many OECD countries. With the state industrializing, income *per capita* is rising quickly, but with it there is growing inequality, with increases in living standards concentrated most in the emerging upper and middle classes.

Figure 1: Location of Punjab, India

The main agricultural crops grown in Punjab are wheat, rice and cotton. Rice is typically planted from May to July and harvested from October to December, wheat is planted in October and harvested from March to May (hence rice and wheat are often planted in rotation), while cotton is planted in May/June and harvested from September/December. A "Minimum Support Price" (MSP) and assured procurement of certain water-intensive crops, particularly rice, incentivizes farmers to grow only select crops, which results in limited crop diversification. The state lies mainly on a fertile alluvial plain, criss-crossed by rivers and an extensive system of irrigation canals. However, there is a belt of hills in the north of the state. The climate is currently characterized by large variations in temperature and rainfall. Winters are cool and dry, the spring is increasingly hot and still dry, summers are very hot and the late summer/early autumn is typically very wet by virtue of monsoon rains (although these rains tend to vary from year to year). Outside the monsoon period, especially in the spring, the state's rivers are mainly fed by meltwater from Himalayan glaciers.

Punjab has emerging problems with water supply/demand. The population is rising, and *per capita* water demand is also rising due to increasing agricultural production, industrial production and household water consumption, especially amongst better-off households. This rising *per capita* demand is not being met by increasing supply, so *per capita* water availability is falling. At the moment, agriculture accounts for around 80% of water demand. 54% of available water in the state is in the form of groundwater. Power subsidies (in the form of nearly a free power supply) to agriculture lines, incentivizes farmers to extract groundwater extensively. There is a simple math to the groundwater situation in the state: groundwater is replenished only very slowly by water trickling down from the surface, and is currently being withdrawn at a much faster rate. According to the World Watch Institute, if the current net rate of withdrawal of groundwater continues, the aquifer under Punjab could be dry by 2025.

The remaining 46% of water is abstracted from rivers, especially for Punjab's extensive irrigation system; about 83% of the state's total land area is irrigated crop land. Large amounts of water are lost from irrigation canals through leakage, especially those that are unlined. In the northern hills, there are some old dams that provide water storage, flood protection and/or electricity supply, although there are also valleys that have yet to be dammed. The Department of Water Resources has been given responsibility by the state government to draw up an adaptation plan for Punjab's water sector, with a time horizon of today to 2050. This plan will focus on water supply, so your life has been made simpler by ignoring flooding issues.

1. **Climate change projections in the region.** Consider how to make appropriate use of climate-model predictions in planning adaptation at the regional level, specifically in Punjab. Look at GCM projections for Punjab and answer the questions below. For this exercise you can rely on the IPCC Interactive Atlas regional information for all of South Asia. This link takes you to a map showing projections for the 2040-2060 time period, with a 1981-2010 baseline, for SSP3-7.0. This corresponds to the information that is requested in the assignment, but you can choose any other scenario or time period you want to support your answers. In particular, look at different emissions scenarios, but try to keep the baseline period (of 1981-2010) fixed since this allows information to be interpreted as the change from the present day. Select the South Asia region to produce time-series graphs of changes, and include one or two relevant ones in your write-up. **Please make sure these are legible in your write-up, and describe / interpret what they are showing!**[1]

   (a) What future changes in climate are projected for South Asia? Look especially at average temperature, max temperature, and precipitation. Pay particular attention to the change in different months, as well as the overall annual average change. Does Punjab look very different from the rest of the region? (6-8 sentences)

   (b) What do you expect would be the consequences for water supply? (1-2 sentences)

   (c) What is the level of uncertainty about future climate predictions in the region, both based on the data you have and based on what you know more generally about the challenges of climate modeling? (2-3 sentences)

   (d) What are the sources of uncertainty? How do these relate to the planning horizon? (1-2 sentences)

   Note that seasonal patterns are important in the region, as you can judge from, for example, the information given above about growing seasons.

[1]Note that there's no convenient way to resize the figure that is produced in the Atlas - you appear to have to manually change the size of your browser window and then export a figure.

2. **Identifying and choosing adaptation options.** Now consider some options to adapt the water sector in Punjab to climate change. Take the information on climate projections into account, as well as background information about current vulnerability, socio-economic trends, etc. Remember we are primarily focused on supply of and demand for water for agricultural, industrial and residential uses, i.e. we are not going to worry about flooding. The list of options in figure 3 might be useful.
   (a) List and explain at least three plausible/promising adaptation options for the region, taking prior info into account. (5-6 sentences)
   (b) How do the adaptation options perform under different plausible scenarios for the future climate of the region, and its future socio-economic circumstances? (2-3 sentences)
   (c) Are these adaptation options robust to uncertainty about future climate change and other pressures? (2-3 sentences)
   (d) Autonomous adaptations are ones which will undertaken by people themselves in response to climate change. Which of your options would be undertaken autonomously and which would require public intervention? Should we expect there to be barriers to autonomous adaptation? (2-3 sentences)

Supply-side	Demand-side
Prospecting and extraction of groundwater	Improvement of water-use efficiency by recycling water
Increasing storage capacity by building reservoirs and dams	Reduction in water demand for irrigation by changing the cropping calendar, crop mix, irrigation method, and area planted
Desalination of sea water	Reduction in water demand for irrigation by importing agricultural products, i.e., virtual water
Expansion of rain-water storage	Promotion of indigenous practices for sustainable water use
Removal of invasive non-native vegetation from riparian areas	Expanded use of water markets to reallocate water to highly valued uses
Water transfer	Expanded use of economic incentives including metering and pricing to encourage water conservation

Figure 2: Source: IPCC AR4 Freshwater resources chapter.

II. Mitigation policy comparison

As a policy-maker, there are a number of tools that you can use to regulate firms' emissions. This question will walk through four such approaches and hopefully highlight how different policies affect firms differently, based on their production levels, profits, and how polluting they are. You will act as the manager of firms that produce "stuff" and your task is to maximize profits. The relationship, in any one time-period (e.g. a year), between profits and the amount of "stuff" produced is given by the following profit function:

$$profit = Ax - x^2 \quad \text{subject to } x \geq 0,$$

where A is your firm-specific productivity factor and x corresponds to the units of "stuff" you produce. The larger your A, the more profitable your firm. Consider four different firms with productivity factors: 10, 20, 30, and 40.

Finding the solution of this optimization problem implies finding the maximum of the profit function above. If you know how to do this using calculus, please do so. BUT you can do so just as well by plotting the profit function and identifying the maximum visually, or computing different estimates of it in Excel. See an example Excel sheet for the "no regulation" scenario, as well as the figure below. For each case you should be able to fill out a table like the example below.

Producing "stuff" causes CO_2 emissions in a one-to-one correspondence. Thus, x units of CO_2 are emitted into the air every x units of "stuff" you produce. An environmental regulator can decide to (i) not regulate your firm, (ii) restrict the amount of CO_2 you can legally emit, (iii) introduce a fixed tax per unit of emitted CO_2, or (iv) allocate you "permits" to emit CO_2 and let you trade such permits with other regulated companies.

EXAMPLE No regulations. In the absence of regulation (i.e. in an emission-unconstrained economy) the one-period profit function corresponds to:

$$A \times x - x^2, \quad \text{subject to } x \geq 0$$

I've completed this case as an example. The table gives the results, and the figure is an example from Excel.

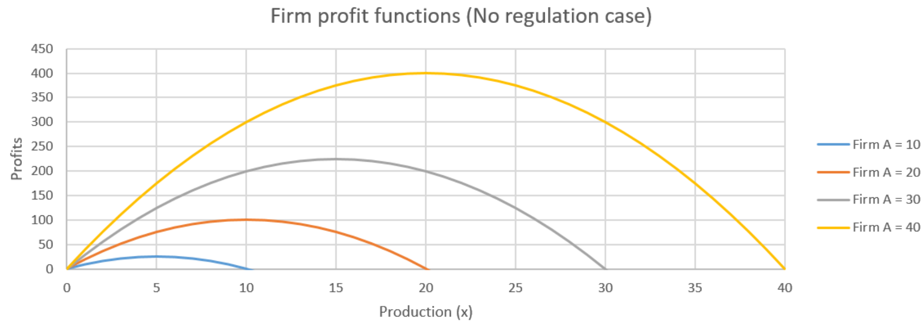

Figure 3: No regulation profit functions of the four firms. The value of x that maximizes profits is the optimal level of production.

	A=10	**A=20**	**A=30**	**A=40**
Optimal output (x)	5	10	15	20
Production profits	25	100	225	400
Total profits	25	100	225	400

1. **Command-and-control.** Suppose now that the environmental regulator allows maximum CO_2 emissions equal to 10 units per firm. The one-period profit function is:

$$A \times x - x^2, \quad \text{subject to } 0 \leq x \leq 10,$$

Under the command-and-control scenario, however, CO_2 emissions are constrained from above at 10 units. Find the optimal production level for each A.

2. **Tax: price control.** Suppose now that the environmental regulator imposes a fixed tax, t, per unit of output. Under this scenario the profit function becomes:

$$A \times x - x^2 - t \times x, \quad \text{subject to } x \geq 0,$$

where t is the fixed tax per unit of output. Suppose $t = 10$ per unit of output. Find the optimal production level for each A.

3. **Market for permits: quantity control.** Suppose finally that the environmental regulator allocates a total of N emissions permits free of charge to each regulated firm and lets companies trade with each other. Each firm must hold one permit for every unit of pollution (and therefore output) it produces. Under this scenario, profits can be generated by production and by trading of permits. The profit function becomes:

$$A \times x - x^2 + p \times (N - x), \quad \text{subject to } x \geq 0,$$

where N is the number of allocated permits and p the price of emission permits. For ease of exposition, let $N = 10$ for every firm and let the permit price $p = 10$. Find the optimal production level depending on A.

4. What is wrong with this market? Does it clear (i.e., are all permits bought and sold in the market)? Does it clear at a permit price of $p = 5$?

5. Summarize the findings. Which scenario has the highest profits? What can you conclude about what the costs of the different regulation for firms? How do profits compare between the command and control versus the tax or the market? Which firms benefit from the permit market case compared to the tax case?