Urban Environmental Equilibrium: Households Location, Water Pollution and Garbage Collection in Port-au-Prince

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Abstract

The density distribution of the population within cities can be mainly explained by a trade-off for households between proximity to the workplace and high housing costs. Yet in households' choice of location, other factors are at play. In a bay like that of Port-au-Prince where downtown is close to the shore and more distant districts are on the heights, runoff waters convey pollution to the most populated areas of the city. This is of importance when garbage collection is almost nonexistent. In this paper, we extend the monocentric city model to account for the environmental costs attached to households' waste and the ensuing water pollution. The derived urban environmental equilibrium is shown to be a great tool for policy evaluation.

1 Introduction

To be written

2 The model

We assume the city center to be on the shore and the populated area to form half a disk. The distance to the city center, x, fully characterizes a location. It determines the height above the see level, $h(x)$, the average price of housing, $r(x)$ (as expressed in *per surface unit*) hence the population density, $n(x)$, the level of environmental externalities, $e(x)$, and the travel costs to the city center, $t(x)$.

For any location as characterized by x, households choose how to allocated their income I, net of transportation costs $t(x)$, between housing and general consumption, c. More precisely, let s denote the surface available to an household. After paying for transportation and housing, it is simple accounting to state that an household may spend up to

$$c = I - t(x) - r(x)\, s$$

for other goods and services.

Let

$$U(c, s, e(x))$$

be the utility function describing the household preferences in terms of consumption, housing and environmental quality. Preferences are continuous, monotonic, increasing and convex in consumption and housing so that U is increasing and concave in (c, s); it is also assumed to be decreasing in the level of (negative) externality e.

Households choices may be represented as a two-steps procedure. First, given a distance to the center x, choose s as to maximize

$$U(I - t(x) - r(x)\, s, s, e(x)).$$

Second, given its maximizand $s(x, I)$ hence $c(x, I)$, choose the location as to maximize

$$U(c(x, I), s(x, I), e(x)).$$

To pinpoint in a tractable model the effect of environmental externalities upon the urban equilibrium, we first wash out two important aspects of the problem. First, we abstract from congestion issues, although they cannot be ignored even by a casual observer. Second, we assume households to have identical preferences, that are homothetic in consumption and housing. This says that the households expenditure shares for both goods depends neither upon their composition nor upon their income. Obviously, this cannot be true, especially in contexts of extreme poverty.

Both congestion and income differentiation have already been introduced in the monocentric city model however. There is no reason to believe that the conclusions drawn from this studies would be invalidated by the introduction of environmental dimension. Neither is there any reason to believe that the environmental effects introduced here would be at play differently if congestion and income differentiation were an ingredient of the model.

Despite the important limitations of this simplified version, our model is able to deliver important policy insights, for urban and environmental planning in general and for garbage collection in particular. For the state regulator, the model provides useful information to help design rules and initiate an institutional innovation process to foster sustainable households' behaviors.

2.1 Determination of the population density profile

Abstracting from congestion does not actually mean that we cannot feed up our model with non-linear effects in transportation and match the data. It simply means that $t(x)$ is imposed at the outset rather than being derived endogenously as a result of the equilibrium population density distribution $n(x)$. It also follows that the density $n(x)$ (or the average housing surface $s(x, I)$) can be directly derived from the knowledge of the transportation costs $t(x)$ and the environmental externality $e(x)$.

In this section, we take the later as given - before to make it endogenous, once $n(x)$ will be known.

Homothetic preferences in consumption and housing result in both $c(x, I)$

and $s(x,I)$ being proportional to the residual income $I-t(x)$ and their ratio depending upon the sole housing price $r(x)$. This says that

$$c(x,I)=\tilde{c}(x)\left[I-t(x)\right] \quad and \quad s(x,I)=\tilde{s}(x)\left[I-t(x)\right],$$

where the share of expenditure devoted to housing $\tilde{s}(x)=1-\tilde{c}(x)$ is determined by the equation

$$\frac{\partial U}{\partial c}=\frac{1}{r(x)}\frac{\partial U}{\partial s}.$$

In follows that, $\tilde{s}(x)$ decreases when $r(x)$ increases, and *vice-versa*. We can also write:

$$U\left(c(x,I),s(x,I),e(x)\right)\equiv U\left(1-\tilde{s}(x),\tilde{s}(x),e(x)\right)\left[I-t(x)\right].$$

Given $r(x)$, $e(x)$ and $t(x)$, households are free to choose their location, as characterized by their distance to the center, x. This says that, at equilibrium, all households settle at their preferred location. It follows that all households with identical income I should reach an identical utility level, whatever their location. In other words, over an area occupied by households with income I,

$$\frac{dU}{dx}=\frac{\partial c}{\partial x}\frac{\partial U}{\partial c}+\frac{\partial s}{\partial x}\frac{\partial U}{\partial s}+e'(x)\frac{\partial U}{\partial e}=0.$$

This can also be rewritten as:

$$\tilde{s}'(x)\left(\frac{\partial U}{\partial s}-\frac{\partial U}{\partial c}\right)+e'(x)\frac{\partial U}{\partial e}=\frac{t'(x)}{I-t(x)}U\left(1-\tilde{s}(x),\tilde{s}(x),e(x)\right). \qquad (1)$$

Given households preferences, as represented by $U(c,s,e)$, the transportation costs $t(x)$ and the environmental externalities $e(x)$, this differential equation makes it possible to the function $\tilde{s}(x)$ hence the density of the population and the price of housing.

A few general comments can be made. First, the larger I, the smaller $t'(x)/[I-t(x)]$, that is the less sensitive the households to transportation costs. It follows that richer households tend to be further apart on the heights while poor households tend to remain downtown. There is also a direct link between distance to the center, housing size and the magnitude of negative externalities. More precisely, being further apart from the center generally means a lower price for housing, hence larger properties and a lower density. If environmental externalities increases as one goes toward the plain (as it is natural if pollution is attached to runoff waters dragging garbage and other pollutants), then the housing price premium attached to the proximity with the center is limited. In other words, there is less of a dispersion in terms of housing prices as the higher transportation costs attached to the distance to the center are already partially compensated by a better environmental quality.

Obviously, the reality is much more complex. In particular, some households, usually poor, don't go downtown to work but are rather attached to the service of rich families on the heights. They tend to live close to those who pay for their services so that housing is more mixed than the model actually suggests. Furthermore, a fragile ground or other variations in geographic or geologic characteristics may yield non-monotonicities in the externality $e(x)$. This may explain that all the poor are not concentrated downtown but some slums actually developed far from the center. Nevertheless, Cité soleil, Delmas, Pétionville, Pélerin, La Boule, Toumassin, Fermathe, Kenscoff...the stylized facts of our model reflect pretty well Port-au-Prince agglomeration.

2.2 Determination of the environmental externalities

Environmental externalities as attached to garbage (lack of) collection and water pollution are multiple. At least three are worth mentioning. First, garbage generation is associated to a local non-point pollution attached to the very household location. Second, heavy rains and the associated water runoff can explain that part of the garbage migrate downhill to other areas. Third, part of precipitations eventually reach ground water reserves and despite the filtration process attached to percolation, it may contains pollutants. To account for all these aspects, we adopt an encompassing formula for $e(x)$, which is at time simplified, when considering one aspect in isolation allows more clear-cut results or an easier interpretation.

Let $g(x)$ be the *per household* garbage generation. The first above mentioned externality is proportional to *total* garbage generation at location x, a function of population density. Formally, we have

$$e_1(x) = n(x)\, g(x).$$

Let $F(x)$ denote the flow of water runoff toward the city center. It's capacity to drag garbage is directly related to the slope of the soil $h'(x)$ as well as other characteristics of the surface of the soil at distance x. We denote by $\eta(x) \equiv \eta[h'(x), x]$ the rate of the flow $F(x)$ that continues its migration toward the center at distance x. At each point, a part of local garbage generation add itself to the flow. We thus have the differential equation

$$-F'(x) = \eta(x)\left[e_1(x) + F(x)\right],$$

with the initial condition $F(\bar{X}) = 0$, where $\bar{X}$ denotes the limit of the city.

As shown in Appendix A.1, it is actually possible to get a simple analytical expression for $F(x)$. More precisely, the water runoff writes

$$F(x) = \int_{x}^{\bar{X}} \eta(v)\, exp\left(-\int_{v}^{x} \eta(u)\, du\right) n(v)\, g(v)\, dv.$$

The second above mentioned externality writes

$$e_2(x) = (1-\eta(x))\left[n(x)\, g(x) + F(x)\right],$$

that is given, given the expression of the water runoff

$$e_2(x) = (1-\eta(x))\left[n(x)\, g(x) + \int_{x}^{\bar{X}} \eta(v)\, exp\left(-\int_{v}^{x} \eta(u)\, du\right) n(v)\, g(v)\, dv\right]$$

Finally, denote by $\kappa(x) \equiv \kappa[h(x), x]$ the proportion of contaminated water that reach ground water reserves through percolation, a function of the distance between the surface and the ground reserves as well as the composition of the soil. All these pollution flows add up in the reserve so that the third above mentioned externality, which impact the whole population independently from its location and writes

$$E_3 = \int_{\underline{x}}^{\bar{X}} \kappa(u)\,(1-\eta(u))\left[n(u)\, g(u) + F(u)\right] du,$$

where $\underline{x}$ is the limit of the city center, *i.e.* the distance from the shore at which housing begins.

The overall environmental externality is an appropriately weighted sum of all these components: $e(x) = \gamma_1 e_1(x) + \gamma_2 e_2(x) + \gamma_3 E_3$.

3 Urban Environmental Equilibrium and Policy implications

Before to enter into the specifications attached to the various type of externalities, it is of interest to look at the general impact of environmental externalities upon the urban equilibrium. As observed before, the very consequence of having (local) negative externalities is that living where they are located becomes relatively less attractive. Thus housing prices tend to decrease, meaning that the average house size increases and that density decreases. Overall, pollution tend to make the population more widespread, hence cities occupying a larger area.

When environmental externalities at a given location are removed, the population becomes more dense at this area. This yields some of the population previously located further away from the city center to move to this area, reducing by doing so their transportation costs. It follows that priority should be given to a reduction of pollution in areas close to the city-center rather than further away. This is indeed what reduces most the overall transportation costs.

To make this argument formal and have a precise view of the redistributive effects of local pollution reduction, the explicit computation of the equilibrium must be done.

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A Appendix

A.1 Computation of the flow of water runoff toward the city center: $F(x)$

By definition, the flow $F(x)$ obeys the differential equation

$$-F'(x) = \eta(x)\left[e_1(x) + F(x)\right], \tag{2}$$

where $e_1(x) = n(x)\,g(x)$ is the local garbage generation and with the initial condition $F\left(\bar{X}\right) = 0$ (where $\bar{X}$ denotes the limit of the city).

Let

$$F(x) = G(x)\,exp\left(\int_x^{\overline{X}} \eta(u)\,du\right).$$

The derivative $F'(x)$can be rewritten as

$$F'(x) = G'(x)\,exp\left(\int_x^{\overline{X}} \eta(u)\,du\right) - \eta(x)\,G(x)\,exp\left(\int_x^{\overline{X}} \eta(u)\,du\right)$$

thus for $F(x)$ to satisfy the differential equation (2), $G(x)$ must satisfy the following differential equation:

$$-G'(x) = \eta(x)\,exp\left(-\int_x^{\overline{X}} \eta(u)\,du\right) n(x)\,g(x).$$

It follows that:

$$G(x) = \int_x^{\bar{X}} \eta(v)\,exp\left(-\int_v^{\overline{X}} \eta(u)\,du\right) n(v)\,g(v)\,dv,$$

since, by definition $F\left(\overline{X}\right) = 0$ hence $G\left(\overline{X}\right)$ must be zero.

Since

$$F(x) = G(x)\, exp\left(\int_x^{\overline{X}} \eta(u)\, du\right),$$

we finally obtain:

$$\begin{aligned} F(x) &= exp\left(\int_x^{\overline{X}} \eta(u)\, du\right)\left[\int_x^{\bar{X}} \eta(v)\, exp\left(-\int_v^{\overline{X}} \eta(u)\, du\right) n(v)\, g(v)\, dv\right] \\ &= \int_x^{\bar{X}} \eta(v)\, exp\left(-\int_v^{x} \eta(u)\, du\right) n(v)\, g(v)\, dv. \end{aligned}$$