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Effect of investments in water supply and sanitation on health status: a threshold-saturation theory*

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A general theory on the relationship between water supply and sanitation investments and health, the threshold-saturation theory, is proposed. The theory takes into consideration three variables: health status, socioeconomic status, and sanitation level, and attempts to encompass, for the first time in one general theoretical framework, numerous conflicting empirical findings. The two-tiered S-shaped logistic form of the relationship that is proposed assumes that at the lower end of the socioeconomic spectrum there is a threshold below which investments in community water supplies and/or excreta disposal facilities alone result in little detectable improvement in health status. Similarly, at the higher end of the socioeconomic scale, it is suggested that a point of saturation is reached beyond which further significant health benefits cannot be obtained by investments in conventional community sanitation facilities.

A preliminary attempt to validate this model using published data on sanitation level (defined as access to water supply), life expectancy, and adult literacy rates, for 65 developing countries, appears to provide preliminary support for the threshold saturation theory but further empirical validation is required before a quantitative predictive model can be developed.

Numerous national and international economic development and technical assistance agencies that are making massive investments in water supply, sewerage, and other urban and rural sanitation programmes in developing countries are properly concerned with the potential health and economic benefits that may result from such environmental improvements.

The agencies involved in this effort have been working on the generally accepted assumption that the provision of an adequate quantity of safe water and proper facilities for the sanitary handling and disposal of human body wastes are basic necessities for the maintenance of good health and productivity. However, despite the fact that this premise has been widely accepted it has been validated quantitatively only in a limited number of well-controlled studies in urban areas and to a varying degree for rural situations. However, an expert panel convened by the World Bank concluded that there was no accepted, reliable procedure for estimating and predicting the health benefits likely to result from such investments.[a]

Cvjetanović & Grab (*3*) have proposed a relatively simple model for rough determination of the costs and

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benefits of sanitation investments on the assumption that a fixed percentage reduction in sanitation-related disease could be established for every new situation on the basis of past experience. Their model was based on the findings of a few published studies that showed different degrees of improved health status in response to investments in water supply and excreta disposal facilities.

Conflicting evidence on the health benefits of sanitation investments has begun to accumulate and has raised some doubts about the validity of such simple predictive models. Saunders & Warford (*9*) reviewed 28 studies on the health effects of water supply and concluded that, in general, the studies provided evidence that improved water supplies were beneficial to health, but gave little help in determining exactly how much improvement in health can be expected.

Four recent epidemiological studies in the Meghna River flood plain area of Bangladesh examined the health effects of the provision of domestic water through hand-pumped tube wells on the incidence of cholera and other diarrhoeal diseases. These studies resulted in what the author calls the "counter intuitive" conclusion that drinking tubewell water was not associated with a reduction in the diseases studied (*1*).

A study by Feachem and colleagues (*4*) in Lesotho found no evidence of disease reduction as a result of a major programme to build village water supplies.

Much concern has resulted from a recent three-year health study in two villages in Guatemala, one with a modern water supply and the other without, that was designed specifically to test the health benefits of village water supply systems. No significant change in diarrhoeal disease morbidity was detected in the test village (*10*).

It is the purpose of this study to attempt to develop a degree of improved understanding of this problem.

THE TWO-PARAMETER MODELS

Most studies so far have attempted to define a relationship between improved sanitation in terms of water supply or excreta disposal facilities and improved health status. This two-parameter approach is schematically represented in Fig. 1. Curve A assumes a straight-line relationship between the degree of sanitation improvement, as might be expressed by the percentage of households with access to safe water or served by sanitary excreta disposal facilities, and improved health status.

Curve B, a hyperbola, is based on the widely accepted economic assumption that as the level of sanitation increases health status rises at a diminishing rate. We considered a further alternative, curve C, which suggests that sanitation improvements will result in improved health status only after a certain mimimum level of investment and then the improvement in health status levels off with further investment to a point of saturation at a diminishing rate of return. However, we consider that the two-parameter approach is inadequate to explain the many anomalies found in studies carried out in areas or countries with very different cultural, social, and economic characteristics.

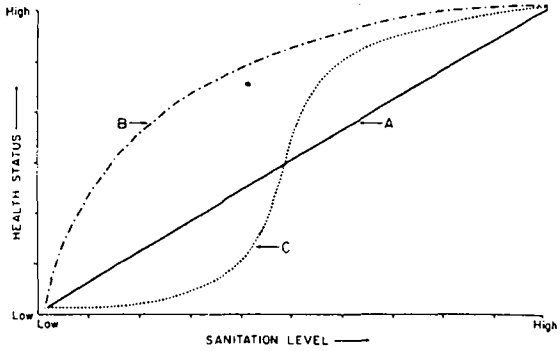

Fig. 1. Two-parameter model of the effect of sanitation on health status.

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A THREE-PARAMETER MODEL

We feel that in order to predict more accurately the degree of health status improvement that may result from given sanitation interventions it is essential in some way to take social, cultural, and economic factors into consideration. Grosse (*5*) has shown that various measures of socioeconomic status are good predictors of health status in developing countries and concluded that the best single predictor of life expectancy at birth is the proportion of the adult population that is literate.

Numerous authors have alluded to the belief that complex social, cultural, and economic factors do play a major role in the responsiveness of communities to sanitation interventions (*1*, *4*, *12*), but little quantitative data is available and the nature of this relationship has not been elucidated.

DEVELOPMENT OF THE NEW MODEL

For the purposes of developing our model, we made a first assumption that under certain conditions of low socioeconomic status (SES) there is no health status

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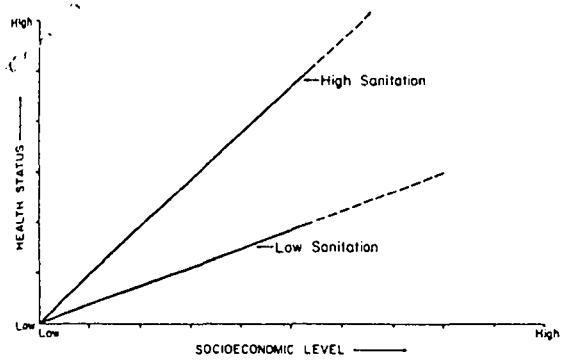


Fig. 2. A three-parameter model of the effect of sanitation on health status at various socioeconomic levels: the "threshold" hypothesis.

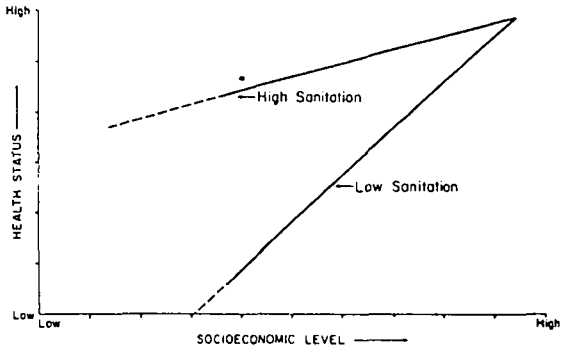


Fig. 3. The "saturation" hypothesis concerning the effect of sanitation on health status at various socioeconomic levels.

improvement in response to a given major improvement in water supply or excreta disposal. This concept (the threshold hypothesis) is presented schematically in Fig. 2. The lower line (low sanitation) represents the increase in health status with increasing SES that occurs even in the absence of any water supply or sanitation improvement project, while the upper line with a significantly greater slope, represents the increasing effect of water supply and sanitation projects on health status with increasing SES levels. The concept assumes the possibility of a threshold effect where at some point the two lines might converge at a very low socioeconomic level. At such a point little or no detectable health status improvement results from an investment in water supply or excreta disposal projects.

An attempt to find some empirical support for this theory was made by analysing the data from a study by Koopman et al. (6) in Cali, Colombia, which included information on water supply and sanitation status, socioeconomic level, and health status in some 2500 households. The findings of this study ran counter to our initial threshold hypothesis (Fig. 2). The Cali data suggested to us the existence, under certain conditions, of a reduced response in the rate of health status improvement as socioeconomic levels increased rather than the contrary. We call this the "saturation hypothesis" which theoretically leads to a point of convergence at the high end of the SES scale, where once again little or no increase in health status is obtained. This hypothesis is presented graphically in Fig. 3.

On further analysis, we took into consideration the fact that Colombia, in general, ranks relatively high among developing countries as regards GNP *per capita* (about US$760) and in adult literacy rate (81%) and that the area under study was in a relatively prosperous region of the country, and concluded that it may be possible to resolve this apparent reversal in the relationship between socioeconomic level and health improvement.

We have assumed that the two hypotheses operate independently over different regions of the SES spectrum, the threshold hypothesis over the lower portion and the saturation hypothesis over the higher portion, with both systems meeting at some intermediate point. The effect of mechanically combining the two sets of curves in the above manner is illustrated in Fig. 4. As a further refinement of this concept we have integrated them both into one continuous logical system, and from this we have developed a general "threshold-saturation" theory that covers the broad spectrum of socioeconomic conditions.

Fig. 5 presents the basic concept of this theory, which is in the form of two logistic curves. The lower one represents situations with little or no investment in water supply and sanitation projects (low sanitation) while the upper curve represents the predicted response in health status resulting from a significant

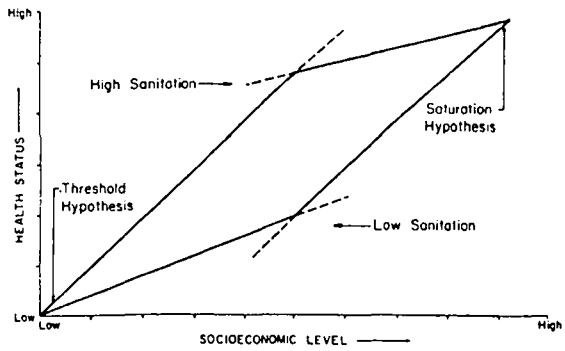


Fig. 4. A combination of the "threshold" and "saturation" hypotheses.

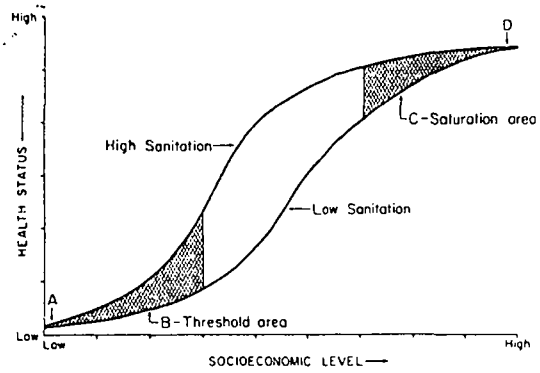


Fig. 5. Schematic presentation of the "threshold-saturation" theory.

investment in sanitation improvement. This model is in a generalized non-quantitative form and is designed to represent the form of the predicted relationships between the three parameters under consideration: health status, water supply and sanitation level, and socioeconomic status. The S-shaped logistic curve has been selected to describe the relationship since it corresponds with the basic concepts associated with other important biological and social phenomena having both threshold and saturation level characteristics. An initial lag phase, or threshold, is proposed for the lowest socioeconomic levels (point A and area B) at which the community is not capable of responding with an improvement in health status to the physical improvements resulting from any environmental intervention (e.g., the provision of water supply or excreta disposal). It is suggested that under such conditions there are multiple and simultaneous routes of disease transmission and that levels of nutrition and personal hygiene are so low that most individuals have low resistance to disease. Reducing this exposure to disease only slightly, say by improving the quality of drinking-water only, as occurred in the Bangladesh studies, would not necessarily lead to any measurable improvement in health status. In other words, it can be said that while community water supplies are undoubtedly necessary to community health, they may not be sufficient to ensure improved health status under certain circumstances. Feachem's studies in Lesotho (*4*) and Briscoe's in Bangladesh (*1*) appear to support this concept. Chenery & Syrquin (*2*) studied ten different economic processes in over 100 countries whose economies were in transition and found that these processes could best be described by S-shaped curves. Their findings provide further support for our choice of the logistic curve form.

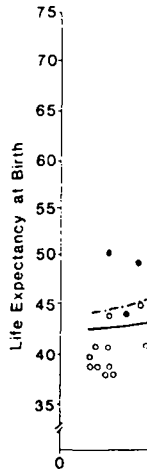
Thus on theoretical grounds alone this theory would suggest that in communities at the lower end of the socioeconomic scale, in the range below the threshold, a prudent health promotion policy would, in addition to water supply, involve the development of an integrated, broad-spectrum programme involving various areas of sanitation, nutrition, education, and primary health care, coupled with efforts to encourage general economic and social development. It suggests that, in some areas, single programme investments, such as the supply of drinking-water alone, may not sufficiently reduce exposure to sources of infection to produce measurable results. It is not the authors' intention to suggest that there should be any reduction in efforts to improve water supplies for such areas. Although health benefits may not be *measurable*, other potential social and economic benefits could by themselves be sufficient justification.

Moving to the right in Fig. 5, as increased socioeconomic levels lead to some general improvement in the standard of living and reduced exposure to infection, we pass the threshold (area B) to a zone of rapid and increasing response to sanitation investments. However, we must assume that at some point to the right, still further up the SES scale, a point of saturation is approached. This area is represented by area C in Fig. 5, which might serve to explain the apparently contradictory findings by Koopman et al. Finally, the theoretical saturation point (D) is reached in communities with very high SES. At this point, we hypothesized that further improvements in health status in terms of reduced levels of communicable diseases and increased life expectancy will result from measures other than improvements in community water supplies and excreta disposal facilities. This, of course, would not apply yet in the developing countries.

PRELIMINARY VALIDATION OF THE THRESHOLD-SATURATION THEORY

We have attempted a preliminary validation of the threshold-saturation theory using published statistics on health status, sanitation levels, and socioeconomic status in developing countries. National statistics on life expectancy at birth were selected as the most reliable measure of health status available (*11*). Although prevalence rates for gastrointestinal disease would have been better, published data on these are much less dependable. The adult literacy rate (*13*) was selected as the strongest proxy indicator of socioeconomic status (*5*) and data on sanitation level were based on published national statistics on the proportion of the urban population having access to water supply by either household tap or standpipe (*8*).

Data from 65 developing countries for the year 1962 are plotted in Fig. 6. The 38 countries with "high sanitation" levels are represented by black circles; in these countries an average of 79% of the homes in urban



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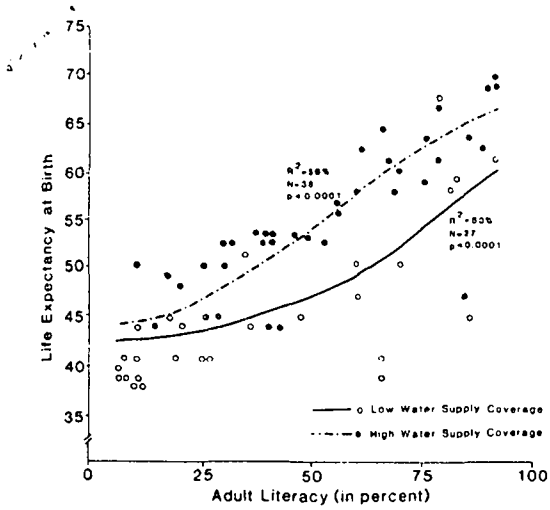

Fig. 6. Relationship between health status and socio-economic level, at two levels of water supply coverage in 65 developing countries.

areas had water taps or standpipes. The open circles represent 27 countries in the "low sanitation" group, in which a water supply was available, on average in 41% of homes.

Visual inspection of the distribution of the data points for the "low" and "high" sanitation countries strongly suggests that the relationships are not linear. An effort was made to determine to what degree the logistic curve configuration hypothesis would fit the data.

The following procedure was employed (*7*):

(*a*) The values of "life expectancy in years" were transformed to values on a scale of 0 to 1 representing the proportion of the maximum attainable life expectancy or the "saturation point". For this, upper limits of 70 years and lower limits (or "threshold") of 38 and 42 years, respectively, were assumed for countries with low and high water supply coverage.

$$S = 1 - U\text{—}LE/U\text{—}L$$

where: U = upper limit
L = lower limit
LE = observed life expectancy
S = life expectancy expressed at % of saturation

(*b*) If the logistic function is a good expression of the relationship between adult literacy and S, then the transformed variable $S' = \log_e S/1 - S$ will be linearly related to adult literacy.

(*c*) To test this assumption, the least squares regression analysis was performed using this transformed dependent variable and measures of goodness of fit were observed.

The tests for the goodness of fit yielded an R^2 of 50% ($R = 0.70$) for the 27 countries with "low" access to water supply and an R^2 of 56% ($R = 0.75$) for 38 "high" countries with $P = <0.0001$ for both cases.

The two fitted curves in Fig. 6 are based on the above calculated logistic transformation. We can assume that because we examined data from only 65 countries there is incomplete convergence at both ends of the curves. Data from more countries would be required to determine the nature of the curves at the extremities.

On the basis of the results of this statistical analysis, it may be stated that the logistic curve form proposed provides a reasonably good description of the distribution of the data points. This cannot be considered proof of the hypothesis, and it does not exclude other curve forms that might also provide alternative descriptions of the data point distribution. At least, we can say that, from this first attempt to validate the threshold-saturation theory, it seems that the data do not appear to conflict with the theory and apparently indicate some tentative empirical support.

It must be recognized that there are serious limitations in the data which were drawn from published statistics on urban areas, some of them of questionable reliability. Nevertheless, despite these limitations, a reasonable impression is gained that the theory does find some support in the real world. More reliable testing of the threshold-saturation theory will require the analysis of cross-sectional and longitudinal data from many different countries, particularly with input from rural areas, and it still remains to determine the appropriate measures of social or cultural development, or socioeconomic status, alone or in combination with other climatic, geographical, or political factors, that will serve as the most reliable predictors of responsiveness to sanitation improvements. Our use of adult literacy rates can be considered only a first approximation of this possibly complex variable.

We hope that the threshold-saturation theory presented in this paper will help to explain some of the reported anomalies as regards the health benefits associated with major investments in community water supply and other sanitation projects. Much work remains to be done in order to provide the degree of validation required to develop a quantitative predictive model. Such a model might be of great use to those planning major water supply and sanitation investments in the developing countries and to health and economic planners in general.

ACKNOWLEDGEMENTS

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RÉSUMÉ

DE L'EFFET DES MESURES D'HYGIÈNE COLLECTIVES SUR LA SANTÉ DE LA POPULATION: THÉORIE SEUIL-SATURATION

Les auteurs proposent une théorie générale sur la relation entre les mesures d'hygiène collectives (adduction d'eau et installations sanitaires) et la santé, selon laquelle il y a à cet égard à la fois un seuil inférieur et un point de saturation. La situation dans trois domaines—santé, secteur socio-économique et hygiène—donne les trois variables prises en considération pour faire la synthèse, pour la première fois dans un cadre théorique général, d'innombrables constatations empiriques contradictoires. La relation ainsi établie (qui se traduit graphiquement par deux sigmoïdes) repose sur l'hypothèse qu'au bas de l'échelle socio-économique il y a un seuil au-dessous duquel, à eux seuls, les équipements collectifs du type adduction d'eau ou installations sanitaires apportent une amélioration à peine décelable de la santé des populations. De même, au sommet de l'échelle socio-économique il y aurait un point de saturation au-delà duquel des équipements classiques de ce genre ne peuvent plus entraîner de résultats bénéfiques notables sur le plan de la santé.

L'essai préliminaire qui a été fait pour vérifier la validité de ce modèle en utilisant des données (déjà publiées) sur le niveau d'équipement sanitaire (défini en termes d'accès à l'eau), l'espérance de vie et les taux d'alphabétisation des adultes dans 65 pays en développement semble, au premier abord, venir appuyer la théorie seuil-saturation, mais il faudra encore faire d'autres vérifications empiriques avant de pouvoir élaborer un modèle quantitatif utilisable pour des prévisions.

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