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MANAGEMENT OF MICROBIAL WATER QUALITY: NEW PERSPECTIVES FOR DEVELOPING AREAS

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ABSTRACT

A case study indicated that the high number of pathogenic micro-organisms in the Rietspruit, South Africa, can impact water uses. Factors contributing to high microbial numbers are high density population with limited services provided per site, sabotage of the sewage reticulation system, lack of money and management skills to provide the essential services and limited integrated development planning for the catchment.

Due to non-steady state conditions in the catchment, the specific use and physical characteristics of the river and the difficulty in determining flow, the usefulness of a steady-state stream water quality model as a management tool is limited. Determining the decay rate of micro-organisms by means of chamber studies, may be a first step to predict microbial water quality. Involving the community in preventing microbial pollution may be a more appropriate tool for microbial water quality management in developing areas.

KEYWORDS

Decay rate; *E. coli*; management; microbial water quality; QUAL2E; rivers.

INTRODUCTION

The transmission of disease by polluted water has a long history and remains a problem to this day. It has been estimated that 50,000 people die daily worldwide as a result of water-related diseases (Schalekamp, 1990). Among the most common water-related infectious diseases caused by bacteria, viruses and parasites are gastroenteritis, amoebiasis, salmonellosis, dysentery, cholera, typhoid fever and hepatitis A. Improvements in waste water disposal, protection of water sources and treatment of water supplies has greatly reduced the incidence of these diseases in developed countries (Craun, 1986). However, in South Africa, with its mixture of developed and developing regions, the problem still exists and may increase as a result of surface water pollution associated with rapid population growth and instructed urbanisation.

Contaminated water not only holds the potential to cause human suffering, but also results in economic loss. An assessment of the cost of water-related enteric illness in developing regions, based on Indian conditions, estimated an average cost of approximately 1700 U.S. dollars per 100 people per annum, with an associated estimate of approximately 1500 days per 100 people per annum (Verma and Srivastava, 1990). Control of water pollution and management of water quality is therefore both an economic and a social responsibility.

All the different water uses are affected by microbiological contamination. The water uses most commonly affected by contamination of surface water are those for potable supplies and for recreational purposes (Thomann and Mueller, 1987). Management of microbial water quality is therefore of paramount importance.

Water quality management in South Africa is primarily the responsibility of the Department of Water Affairs and Forestry (DWAF), although the Department of Health oversees health aspects. The water quality management policies of DWAF were, until recently, based on the formulation of uniform effluent standards which were set without regards for the quality of the receiving water body.

Recent policy changes in the department have resulted in a movement toward quality management by receiving water quality objectives (RWQO), with the aim of maintaining the "fitness for use" of waterbodies. This approach recognises that water has a definable assimilative capacity for pollutants, i.e. water has a limited capacity to absorb, degrade and/or transform pollutants without deterioration of water quality to the extent that the fitness for use of the water body becomes impaired. Pollutant loads which can be discharged to a water body therefore depend on the total number of polluters and on the ambient water quality. The site-specific nature of many water pollution problems, and hence the inadequacies of uniform effluent standards as a means to manage such problems, are hereby recognised (DWAF, 1991).

Management by RWQO encompasses compilation of water quality management objectives which recognise the water quality requirements of users as well as economic, social, political, legal and technological considerations. Site-specific effluent standards or other measures are imposed to ensure that the water quality management objectives determined for a particular water body are met. This approach has been applied to chemical and physical water quality variables in several instances, but has yet to be applied systematically to microbial water quality variables. The institution of monitoring and information systems for microbial water pollution, and particularly the development of approaches and policies to manage the impact of non-point source inputs of microbial pollutants, are recognised as high priority needs by DWAF (DWAF, 1991).

Microbial quality of surface water bodies in South Africa is currently controlled by regulation of the microbial quality of effluents discharged, on *Escherichia coli* (*E. coli*) levels of nil organisms/100 ml with exemptions in specific cases. No instream standards exist. The processes of dilution and die-off of microbial pollutants and the assimilative capacity of rivers for these pollutants are assumed to be adequate to safeguard the microbial quality of water bodies. It is further assumed the *E. coli* levels adequately reflect the presence of all microbial pathogens.

This paper will clearly show that if management of microbial water quality is not applied for 100 percent of the time, it is very dangerous for most water uses. The paper will also discuss the role of microbial water quality modelling and the determination of microbial decay rates in developing areas for water quality management.

MATERIALS AND METHODS

In a joint research venture, Rand Water, CSIR and the Water Research Commission launched a project in 1991 to study the microbial water quality in the Rietspruit catchment, a small (1120 km^2), densely populated catchment (1000 people/km^2) containing developed and developing areas. The river draining the catchment is dominated by inputs of treated sewage and mine water. Due to the lack of maintenance of infrastructure and the political climate for several years, specific sections of the catchment experience sewer blockages on a frequent basis. The latter complicates microbial water quality management, because waste water treatment plant management query the validity of strict effluent quality control when nothing obvious is done to solve the diffuse source pollution.

The sample points selected for the study were up and downstream of tributaries and point sources (Figure 1). For this paper, results from only the sample points just above a sewage works (RKRA) to the end of the catchment (RV2) was used for the modelling exercise, although faecal coliform results for the whole river are presented.

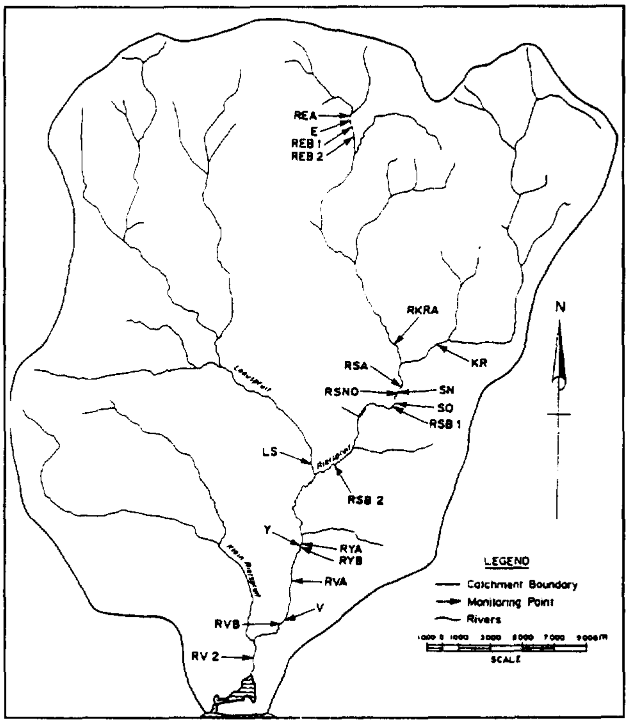

Figure 1. Location of the Rietspruit catchment and sample points used.

Continuous flow records were only available at a weir, RV2, at the downstream end of the Rietspruit, thus complicating the modelling exercise. Flows at the river sample points, therefore, had to be calculated by means of velocity measurements at a number of water levels, relative to a fixed point on the river banks. Effluent volumes discharged at the time of sampling proved to be not accurate and had to be calculated, using a mass balance.

Although several physical, chemical and biological analyses were done, faecal coliform results will be presented and used for modelling. Faecal coliform determinations were conducted using a membrane filtration technique (APHA, 1985).

It is not clear how applicable models developed to manage microbial water quality conditions in the United States of America (USA) or Europe, are to South Africa. As part of the research project, the QUAL2E stream water quality model (Brown and Barnwell, 1987) was tested as a management tool.

Modelling of instream microbial water quality, as a consequence of inputs to the river, depends heavily on the choice of microbial decay rate constant which describes the die-off of micro-organisms over time. During the first part of the study, decay constants were selected on the basis of values provided by the United States Environmental Protection Agency (USEPA), derived predominantly from studies conducted in the USA. It was initially hoped that these could be adapted for the purposes of this investigation. However, values are not necessarily applicable to local conditions, particularly in view of the differences between rivers in the USA and in South Africa. In any given catchment the level of microbial contaminants is influenced by the unique environmental factors, e.g. the chemical and biological quality of the water, temperature and pH. In this study the combined effect of environmental factors on the fate of bacteria, such as *E. coli* in the Rietspruit catchment, was determined by *in situ* membrane diffusion chamber studies. It was also of importance to evaluate the chamber study results as a standalone tool for microbial water quality management.

Two sites in the Rietspruit were selected to do chamber studies. Sample point RSB1, situated downstream of a sewage discharge, is dominated by domestic discharge and diffuse source run-off. The second point, RYB, is situated downstream of an industrial discharge, receiving steel industry effluent, underground mine water as well as water from RSB1 (see Figure 1). For comparison, a chamber was submerged in water from RSB1 under controlled flow and temperature conditions in the laboratory. Test runs were performed during winter (July 1993) and summer (December 1993) months.

An *E. coli* strain was isolated from treated sewage discharged into the Rietspruit catchment at RSB1 and was confirmed using standard biochemical tests (Gerhart *et al.*, 1981). The isolate was finally identified as *E. coli* on the API 20E identification system (bio Merceux Su, France). For the preparation of the inoculum, the *E. coli* strain was grown in trypticase soy broth supplemented with 0.3 percent yeast extract and 0.5 percent glucose at 37°C for 24 hours. The bacteria were harvested, washed twice with phosphate buffered saline (PBS) and resuspended in filter sterilised river water. The chambers were each inoculated with 100 ml of this inoculum, which had a final concentration of ± 10^{10} cells/100 ml.

Stainless steel diffusion chambers, based on the design of McFeters and Stuart (1972), were used. Polycarbonate membrane filters (Nucleopore, pore size of 0.2 µm) were used. Sterile chambers were assembled aseptically and filled with the inoculum. The two chambers destined for the *in situ* experiments were transported to the selected sites in 25l of river water. The river water in the vessel used in the laboratory study was replaced on a regular basis.

During the winter study (July) the chambers were sampled at zero hours and thereafter at daily intervals over a period of 12 days (except days five, six and eight). During the summer (December) the chambers were sampled at daily intervals for the first 12 days (except day five, six and ten) and thereafter three times a week for the next four weeks if practically possible. The samples were enumerated using the membrane filtration technique and mFC agar (APHA, 1985). The blue colonies isolated were confirmed as *E. coli* by testing for indole production at 44.5°C.

RESULTS AND DISCUSSION

Figure 2 presents a graphic summary of the faecal coliform numbers in the Rietspruit for a two-year period (1991 to 1993). A step increase in the faecal coliform numbers is observed downstream (RSA) of the confluence of the Rietspruit (RKRA) with the Kleinrietspruit (KR). The Kleinrietspruit drains a developing area in which frequent sewer blockages are recorded, which explains the high faecal coliform numbers in the water. The Leeuwspruit (LS) draining agricultural areas, in which underground mine water is discharged, seems to be responsible for lower faecal coliform counts downstream of its confluence with the Rietspruit (RYA). Treated domestic sewage effluent (V) discharged upstream of the end point of the river is responsible for the bigger variance in faecal coliform counts at points downstream thereof.

Figure 2 also indicates the South African recreational guidelines value (DWAF, 1993), above which the risk of contracting gastro-intestinal illness as a result of full contact recreation increases. This guideline also implies a decrease in the volume of water ingested in order to cause adverse effects as the faecal coliform density increases. From Fig. 2 it is evident that densities of faecal coliforms at most of the points in the river are higher that the guideline value of 2000 org/100 ml. It is also evident from Fig. 2 that the change in faecal coliform numbers in the Rietspruit is not only a function of microbial decay but is largely affected by inputs into the Rietspruit by the Kleinrietspruit and the Leeuwspruit. It is also of interest to note that except for Ennerdale sewage works (E), all the other sewage effluents seldom comply to the zero org/100 ml requirement for faecal coliforms.

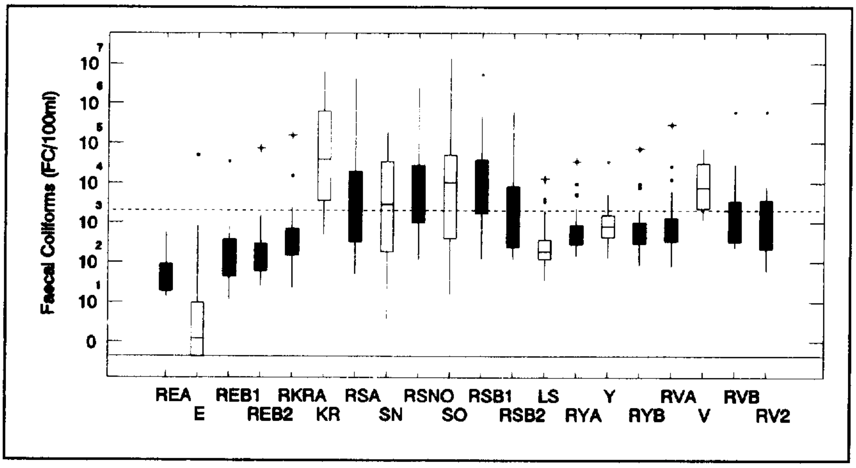

Figure 2. Faecal coliform numbers at different sample points in the Rietspruit in relation to the 2000 org/100 ml recreational guideline.

The water of the Rietspruit is used by the local inhabitants for bathing, washing clothes, fishing and agriculture. It has also been recorded that several of the inhabitants use water directly for potable purposes. Because of the specific use of the water and the high density of faecal coliforms, authorities in the catchment expressed their concern regarding the health implications associated with the use of the water.

To evaluate whether specific management strategies will result in the desired faecal coliform densities, water quality modelling may be required. For this purpose the QYAL2E model was selected. In some instances the QUAL2E model was able to predict the faecal coliform count (Figure 3). Unfortunately the model could in most cases not predict faecal coliform counts accurately (Figure 4) although in both cases a decrease in faecal coliform counts was indicated.

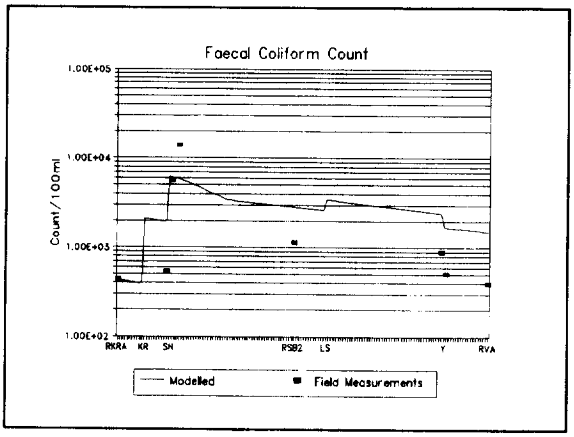

Figure 3. Predicted and actual faecal coliform counts as of 21 January 1992.

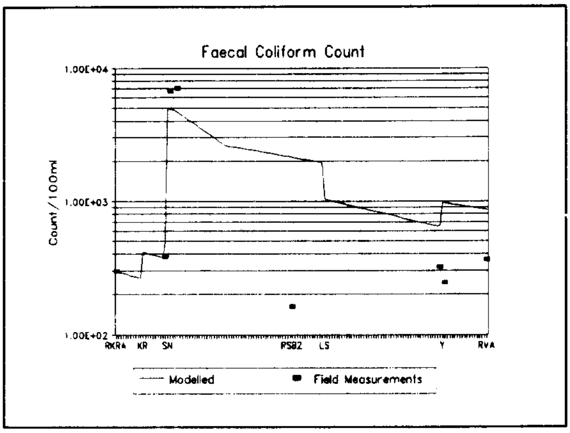

Figure 4. Predicted and actual faecal coliform counts as of 19 May 1992.

Several possible reasons were identified why the QUAL2E model could not be used to successful predict the faecal coliform counts in the Rietspruit. The most important reasons were the following.

- The flow in the river varied with time due to time-varying discharges by the sewage works.
- On some days the sewage works chlorinated the effluent and other days not, which had a marked effect on the faecal coliform load discharged (Figure 5).

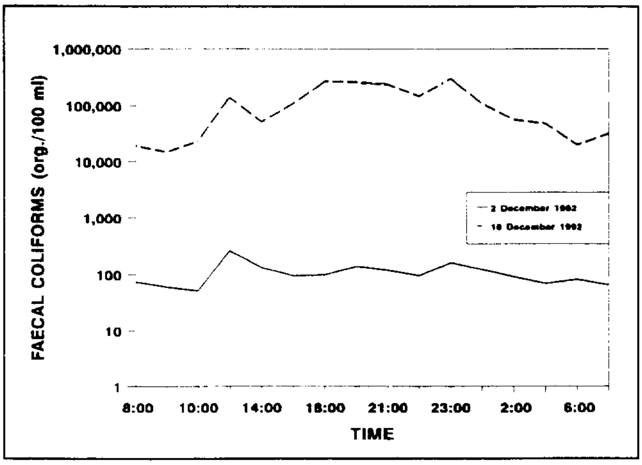

Figure 5. Faecal coliform counts of chlorinated treated sewage effluent (2 December 1992) vs unchlorinated effluent (10 December 1992).

If samples are therefore not residence-time coupled, outliers such as the faecal coliform count at RSB2, downstream of a sewage discharge, may be recorded. Initial assumptions on steady state conditions in the Rietspruit were not correct, thus contributing to the QUAL2E model not performing that well. As time, manpower and logistics did not allow for residence-time coupled sampling a subproject was formulated to determine the decay rate as a standalone tool for management of microbial water quality. For the purpose of this paper only the decay rate studies are discussed.

Measured faecal coliform values were plotted and a regression line determined for each of the stations. The first-order decay rate constants for each station were then determined based on the slope of the regression line (See Table 1).

As can be seen from Figures 6 and 7 as well as the results in Table 1, the decay rates obtained for the two stations are very similar. As may be expected, the decay was slower during the summer run, being 14 percent and 18 percent lower at RYB and RSB1 respectively.

A comparison between the results obtained from this study and values reported (Bowie *et al.*, 1985) showed that these decay rate constants were within expected norms.

Some examples are:

- North Fork King River (California)	k: 1.008 (1/day)
- Boise River (Idaho)	k: 0.48 (1/day)

Shallow, more turbulent streams, could have decay rate constants as high as 15 to 24/day. Discussions with Tom Barnwell (personal communication) of the USEPA Environmental Research Laboratory, indicated that "typical first-order decay rates for coliforms are in the order of 1.0/day".

It is of interest to note that the survival of *E. coli* observed in the study performed in the laboratory followed the same pattern noticed for the *in situ* studies performed at the two sites in the river (Figure 8). This could imply lowering the risk of losing chambers in the river still obtaining decay rates representative of that in the river.

Table 1. Decay rate constants at different points in the Rietspruit

	Station RSB1	Station RYB
Winter run: 5 - 16 July 1993:		
Decay rate constant, k(1/day)	0.975	1.075
Decay rate constant, k(1/h)	0.041	0.045
Half life (days)	0.711	0.645
Summer run: 6 December 1993 - 14 January 1994:		
Decay rate constant, k(1/day)	0.800	0.925
Decay rate constant, k(1/h)	0.033	0.039
Half life (days)	0.866	0.750

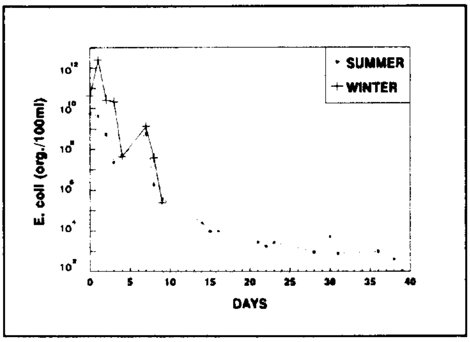

Figure 6. Decay of bacteria in a chamber suspended in the Rietspruit after the confluence with purified sewage effluent.

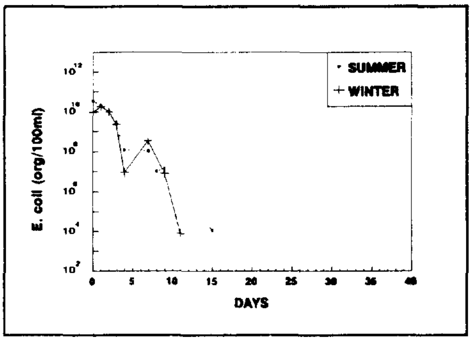

Figure 7. Decay of bacteria in a chamber suspended in the Rietspruit after the confluence with purified industrial effluent.

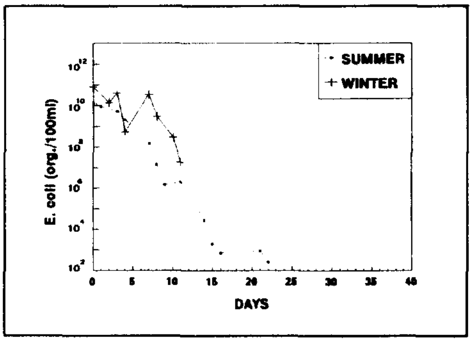

Figure 8. Decay of bacteria in a chamber suspended in a circulator filled with Rietspruit water obtained after the confluence with purified sewage effluent.

IMPLICATIONS FOR MICROBIAL WATER QUALITY MANAGEMENT IN DEVELOPING AREAS

From the above information it may be concluded that the simple first order decay model may not be adequate to accurately simulate coliform decay in the river like the Rietspruit. In this study, the largest impacts on the coliform counts in the river were as a result of point source loading or as a result of dilution with less microbial loaded sources and not only as a result of die-off.

In rivers showing similar characteristics and catchment activities as at the Rietspruit, a holistic approach to microbial water quality management is suggested. This implies the setting of receiving microbial water quality objectives above and downstream of point and diffuse source inputs. It also implies optimal use of waste water treatment technology, knowledge of the residence time in different reaches of the river as well as the decay rate of microbial organisms. If the decay rate indicates insufficient die-off of bacteria before the water arrives at a specific point in the river, the following unconventional management approaches are suggested.

- Point sources, contributing to a major portion of the flow in the river (as in the Rietspruit) should be limited to a "zero" faecal coliform discharge. This could dilute faecal coliforms instream.

- Low level technology such as constructed wetlands or maturation ponds to contain a treat raw sewage spillage should be implemented in areas with a high population density with limited services, in which wilful sabotage of sewage reticulation takes place and where lack of money and management skills are evident. Participation, ownership and ongoing involvement of the community will be of paramount importance to reduce faecal pollution to such limits that dilution by point source discharge or other "non-polluted" inputs will have the desired result.

ACKNOWLEDGEMENTS

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REFERENCES

APHA (1985). *Standard Methods for the examination of water and waste water.* 16th Edition, American Public Health Association, Washington D.C.

Bowie, G. L. Mills, W. B., Porcella, D. B., Campbell, C. L., Pagenkopf, J. R., Rupp, G. L., Johnson, K. M., Chan, P. W. H., Gherini, S. A. and Chamberlin, C. E. (1985). *Rates, constants and kinetics formulation in surface water quality modelling,* 2nd Edition, USEPA, Athens, Georgia.

Brown, L. C. and Barnwell, T. O. (1987). *The Enhanced Stream Water Quality Models QUAL2E and QUAL2E-UNCAS: Documentation and User Manual.* EPA Document EPA/600/3-87/007. Environmental Research Laboratory, Office of Research and Development, *U.S. Environmental Protection Agency,* Athens, Georgia, USA.

Craun, G. F. (1986). *Waterborne Diseases in the United States.* CRC Press, Inc., Boca Raton, Florida.

Department of Water Affairs and Forestry, (1991). Water Quality Management Policies and Strategies in the RSA. Pretoria, South Africa.

Department of Water Affairs and Forestry, (1993). *South African Water Quality Guidelines. Volume 2: Recreational Use.* Pretoria, South Africa.

Gerhart, P., Murray, R. G. E., Ootilow, R. N., Nootor, E. W., Wood, W. A., Krieg, N. R. and Phillips, G. D. (1981). *Manual of methods for general bacteriology.* American Society for Microbiology, Washington.

McFeters, G. A. and Stuart, D. C. (1972). Survival of coliform bacteria in natural waters: Field and laboratory studies with membrane filter chambers. *Appl. Microbiol.*, **24**, 805-811.

Schalekamp, M. (1990). The UNO-drinking-water decade 1980-191: Problems and Successes. Lecture held on the occasion of the 100th Anniversary of the Austrian Gas and Water Industry. Water Supply Zurich, Industrial Corporations of the City of Zurich. Bombay.

Thomann, R. V. and Mueller, J. A. (1987). *Principles of Surface Water Quality Modelling and Control,* Harper and Row Publishers, New York, USA.

Verma, B. L. and Srivastava, R. N. (1990). Measurement of the personal cost of illness due to some major water-related diseases in an Indian rural population. *International Journal of Epidemiology*, **19**(1), 169-176.