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INVESTMENT CRITERIA AND MATHEMATICAL MODELLING TECHNIQUES

FOR WATER RESOURCES PLANNING IN ARGENTINA: THE MIT-ARGENTINA PROJECT

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INTRODUCTION

The objective of this paper is to describe a research program at MIT (USA) for the application of modern investment criteria and mathematical modelling techniques for water resources planning in Argentina. The project lasted for two years and had three principal objectives: (1) to adapt modern water resources planning techniques to Argentina; (2) to train Argentine professionals in the use of these techniques; and (3) to apply the techniques to a basin in Argentina for the purpose of developing alternative management and development plans for the river responsive to alternative economic and social objectives.

In considering the use of systems techniques in developing countries, the organization of programs to apply them; the nature of the available techniques; and applications of them are all of interest and importance. Accordingly, in this paper key organizational features of the MIT-Argentina program are described; the nature of modern water resources planning methods is outlined; and the system of models developed for the case study is described. Finally, a few tentative conclusions about the study are presented.

ORGANIZATION OF THE STUDY

The organization of the study was developed jointly by MIT personnal and Argentine representatives of the State Subsecretariat for Water Resources of Argentina, a subcabinet agency that was newly created in Argentina in 1970 to bring together formerly uncoordinated water resources planning activities in the Federal government. The study team consisted of five MIT professors in Civil Engineering, representing diverse professional backgrounds from hydrology to economics; a full-time project manager (a recent MIT Ph.D. in Civil Engineering); six young Argentine professionals who came to MIT as Visiting Research Engineers for the duration of the program; and graduate and undergraduate research assistants. The substantive work of the program was completed in the period from 1 September, 1970 to 30 September, 1972.

A program report has been prepared, consisting of several main volumes on general methodology, recommendations for Argentina, and the results of the case study; and numerous technical appendices with detailed model formulations and data sources. The report is being translated and reviewed during the 1972-73 academic year, and it is hoped that it will be publicly available late in 1973.

Two organizational aspects of the program will be of particular interest to this Conference, both because they reflect the nature of the program well and because they might serve as models for other programs in technology transfer. One aspect is the training of the group of six young Argentine professionals at MIT, and the other is the extensive contact that took place between MIT and Argentine professionals in Argentina and the USA.

The presence of the six young professionals as Visiting Research Engineers at MIT was part of the teaching function of the project. Each of these men agreed to come to MIT and then to work for three years for the Subsecretariat, thus guaranteeing the new agency a corps of well-trained systems professionals. At MIT they took courses ar participated fully in the development and planning of the research. The group, consisting of economists and engineers, is now fully capable of further developing and utilizing the system of models constructed for the case study, and of developing other sets of models for other water resources planning programs in Argentina. The effect of this aspect of the program was to present the Argentine government with a "living report." To facilitate the work of these men after their return to Argentina, all of the models developed for the case stuc were designed so that they can be run on computational equipment currently available in Buenos Aires.

The second organizational aspect of interest is the extensive contact that took place between the research group and the Argentine sponsors of the contract and other Argentine professionals. This was also a planned part of the program, and it took several forms. One clause in the contract provided for 15 round trips per year for MIT personnel between Boston and Buenos Aires. These trips were used to gather data, to discuss technical questions, and to discuss Argentine planning objectives with

Argentine decision-makers and their aides. During one of these trips, the MIT professors presented a short course in applied systems techniques for water resources planning in Neuquen, Argentina, in August, 1971. About 40 Argentine professionals attended this conference. During other trips, numerous visits to the case study basin itself were made for field inspections of the river and irrigation areas and for discussions with local and provincial officials. In the second year of the contract, when the models had been completed in their initial forms and the first runs were made, a counterpart group of technicians from the riverine provinces in the case study basin was formed to review models, assumptions, and the trial results of the models. In addition Argentine water officials made several trips to MIT to discuss the research and to make inputs to the case study.

WATER RESOURCES PLANNING METHODS

Water resources planning methods are many and various. However, two central elements of modern planning methods in this field can be identified: multiobjective planning, and the use of mathematical programming models and hydrologic simulation models in tandem. Both of these techniques date from the principal research report, published in 1962, of the Harvard Water Program.(1) Multiobjective planning will be described first.

Benefit-cost analysis for water resources planning was developed after the Second World War.(2) This analytic technique focussed on the net contributions of projects to the national income. However, most water resources and other public projects are undertaken for a variety of social, environmental, defense, and economic and other objectives, so that a method of analysis that concentrates on only one of these objectives (increasing national income) leads to less than optimal programs in social terms.(3) This tension is resolved when programs are explicitly planned in terms of their benefits and costs toward all objectives; in water resources terminology, this is multiobjective planning. (It is to be distinguished from the more familiar multipurpose planning. Purposes are, for example, navigation and water supply; the objectives to which these might contribute are regional income, national income, defense and others.) ~~The~~ theory can be depicted graphically, as in Figure 1. Here, the objectives are national income and income gains to a selected, perhaps underdeveloped, area of a country. Benefits are net and discounted. Rules for counting regional income are different than for national income, since regional income includes domestic transfer payments and national income does not. If one conceives of a set of social preference curves, the optimal point for any planning problem is the tangency between the boundary of the feasible set of net benefit combinations and the highest attainable social preference curve. Details can be found in Marglin (4) or Major (5). Multiobjective planning has been recommended for all Federally financed water projects in the USA (6) and a recent UNIDO publication (7) embraces this approach.

The second aspect of methodology is the combined use of mathematical programming models and hydrologic simulation models. River systems and other water systems are complex and tend to be stochastic. Simulation models can be used to analyze the effects of stochastic hydrology on detailed representations of proposed system configurations and operating policies. However, these models are not adequate by themselves for planning because they are not useful for preliminary screening of alternative system configurations to select those that appear good enough to repay detailed analysis. For this purpose mathematical programming is used. While mathematical programming models are not well suited to the detailed stochastic system representation provided by simulation models, they are well adapted to the preliminary screening function. A water resource system can be represented by a mathematical programming model, albeit somewhat crudely, in economic, social, physical, and hydrologic terms. The analyst takes advantage of the formal maximizing capabilities of such a model to select alternative configurations that are optimal in terms of alternative objectives and alternative assumptions about data inputs to the system. These configurations are then used as starting points for detailed analysis in a simulation model.

Modern water resources planning methods embrace criteria and techniques other than those cited and for these reference can be made to (1) and (4)

THE CASE STUDY

The basin selected for the case study was suggested by the Argentines. The Rio Colorado (Figure 2) rises from snow-melt runoff in the Andes and runs for about 900 km through arid country to its mouth in the Atlantic, about 125 km south of the grain exporting port of Bahia Blanca. The mean annual flow of the river is about 120 m^3/s. Although this is a small river, the distribution of water in Argentina is such that, aside from the giant group of rivers forming the Plate Basin, the Colorado is one of the largest rivers in the country. The present population of the basin is not more than 50,000 persons. The river runs through parts of five Argentine provinces: Mendoza, Rio Negro, Neuquen, La Pampa, and Buenos Aires Province.

The river, because of the lack of tributaries in the middle and lower reaches and sparse rainfall in the basin, is a relatively simple hydrologic entity. It can be related by man-made transfers to rivers to the north and to the south. To the north, exports are possible to areas in the relatively wealthy old province of Mendoza, which has as a principal industry the growing of wine grapes in irrigated areas. To the south, imports to the Rio Colorado are possible from points in the Rio Negro system.

The principal purposes of development on the river at present are for creating and enlarging irrigated zones and for producing power. The river is not now regulated, although water is diverted for irri-

"Superior numbers refer to similarly numbered references at the end of this paper."

gation at several sites. The only substantial long-established irrigation area is at Pedro Luro near the mouth of the river. Several newer areas are under development further upstream.

The river is an interesting case study from the point of view of multiobjective decision-making, because each of the five riverine provinces has interests somewhat different from those of the others and from those of the national government. Since some of the riverine provinces or some areas within them have few resources aside from the river; given the historic importance of irrigation to many areas of Argentina; and given the plans that the separate provinces have for development that would if all brought to fruition require water in excess of the capacity of the river; the decision problem is of great practical as well as theoretical interest.

MULTIOBJECTIVES IN THE CASE STUDY

A substantial effort was made to investigate the range of relevant objectives for the develoment and management of the Rio Colorado. Two examples among many can be given. During the short course mentioned above the MIT team asked the attending professionals for their views on objectives for the Rio Colorado. This produced a list of nine objectives. As a second example, the existing commission for the Rio Colorado, in an important document (8), listed the points of agreement and disagreement among the provinces as to the objectives of developing and managing the river. The MIT team discussed this document with Argentine professionals and toward the end of the project made a formal presentation to the counterpart group of the provinces as to the MIT team's interpretation of each clause of the document. The objectives that were developed from all sources can be categorized generally as aspects of the national or regional economic development objectives. (For categorizations of objectives see (4) or (6).)

The models developed for the Rio Colorado case study reflected the planning team's attempt to integrate the objectives of the Argentines with the technical possibilities of the river, or in terms of the diagram in Figure 1, the social preferences with the net benefit possibilities of the system. Although detailed numerical illustrations cannot be given before formal approval of the program, a description of the system of models used will make the case study techniques clear.

THE SYSTEM OF MODELS

A series of three models was used to generate the alternative programs presented to the Argentines as the case study output of the project. Other models and estimating techniques were used for special purposes in the research, including the generation of data inputs for the three models used to develop alternative programs. The series of models incorporates the ideas about objectives that were derived from the process described above, and each of the final configurations reflects a particular mix of objectives.

The series of models includes first a mathematical programming screening model of the type described above. The purpose of this model was to find configurations that could be tested for hydrologic feasibility by the second model, the hydrologic simulation model. The results of this model were utilized in a mixed integer "sequencing" model to develop the appropriate scheduling of hydrologically feasible projects over time.

The screening model is formulated for two purposes, irrigation water supply and power production, and in terms of the several dozen potential dams, irrigation areas, power stations, and import and export sites on the river. A steady state hydrology is assumed: the mean flow historically for each of three seasons is assumed always to prevail in that season. The number of seasons is determined by the characteristics of irrigation and power demands. The non-linear functions in the model are approximated by piecewise linear functions. Some of the benefit and cost functions have curvatures such that global optima are not guaranteed. Originally formulated without integer variables, the model was used for production runs as a mixed integer programming model with about 900 variables, including 8 zero-one integer variables representing initial costs for dams, and about 600 constraints. The model is run using the IBM MPS-X package on the Harvard-MIT computation center IBM 370/155 computer system. The cost of a run is about US $70. A large number of runs was made with this model in one or another of its forms during the course of the project.

Objectives were incorporated either into the objective function or as constraints on the system. One objective function formulation was to maximize net discounted national income benefits plus weighted discounted net regional income benefits for each of the five provinces. An example of a constraint formulation of objectives is that in which an upper limit on power production was used to reflect the provincial objective of emphasizing irrigation. Detailed methodological results of the use of the mathematical programming model for multiobjective screening are given in (9).

The most promising configurations from the screening model, consisting of optimally-sized works for power, irrigation, and imports and exports, were run on the hydrologic simulation model of the Rio Colorado. This permitted these configurations to be evaluated in terms both of stochastic hydrology and of the operating policy built into the simulation model. (An operating policy in a model of this type fulfills such tasks as allocating flows in years of shortage.) As a result of runs by the simulation model, the configurations from the screening model could be altered to insure that they were hydrologically feasible, and the benefits and costs toward objectives of these hydrologically feasible configurations could be estimated.

The simulation model runs on seasonal (4-month) flows, and for a run of 50 simulated years costs US $10 to operate.

After the hydrologic feasibility of configurations is tested on the simulation model, and any warranted changes in project scale and location are made, the results are run in a "sequencing model", the third and last of the three models used to generate program alternatives for the case study.

Optimal scheduling of projects over time is a relatively neglected aspect of water resources planning. It has been common simply to bring projects on line when needed to meet various projections of physical output needs without regard to the effects of scheduling on discounted net benefits. This approach is often referred to in engineering practice as "staging." However, for optimal planning it is necessary to examine in terms of net benefits not only every configuration but also every potential schedule for implementing each configuration.[10] This has not been done for water resources planning, but an attempt was made in this study to deal with aspects of the problem by building the sequencing model. The purpose of this model is to take the configuration of projects that has been run on the simulation model, and is thus hydrologically feasible, and to schedule the projects optimally in four future time periods taking into account benefits over time, budget constraints, constraints on the number of farmers available to work new irrigation areas, and project interrelationships such as the necessity to insure that an irrigation area is not built without a dam to supply it. It is the output of this model that constitutes a program alternative for the Rio Colorado. The sequencing model has about 60 continuous variables, 120 integer variables, and 110 constraints depending on the exact configuration that is being modelled. To get very close to the optimal solution with this model costs U$ $15.

OTHER MODELS

In addition to the three models just described other models were built in the course of the research, either for specific purposes relating to the Rio Colorado study or for general methological purposes relating to the study of water resources planning methodology as it applies to Argentina. Detailed simulation models were built of several aspects of the Rio Colorado system, including a snow-melt run-off model and a model of the hydrology and economics of an irrigation area. Another model of interest is a systems dynamics model based on Forrester's techniques.[11] This was used to study migration to new irrigation areas in Argentina. In addition, many other special-purpose models and programs were constructed; these are all listed in the research reports of the project.

CASE STUDY RESULTS

While the alternative programs that were generated for the Rio Colorado are still under review and thus are not publicly available, it can be said that the results of the case study pose interesting questions in social choice as between alternatives responsive to different objectives and different assumptions as to data inputs. Given objectives and assumptions, possible configurations range from little or no development of the river to essentially full development, including different combinations and locations of power plants, irrigation sites, and imports and exports. In the case study results Argentine decision-makers have a picture of the choices to be made in the Rio Colorado. Further, with their group of trained professionals they are in a position to consider any additional assumptions and objectives that are of interest to them; and after initial development takes place they will be able to monitor the system continuously with the series of models to assure regular updating of the development configuration chosen for the river.

CONCLUSIONS

While it is too early to say definitely, it appears that the MIT-Argentina project might constitute a successful transfer of systems technology from one country to another. Argentina is a country at a middle level of development, but some of the features that appear to have been important to the potential success of the program described here might serve as models for programs for the transfer of systems methods to less developed nations.

First, the program was initially proposed by the host country, and was jointly structured by MIT and Argentine personnel, on the basis of a mutual awareness of the nature of the specific technology to be transferred.

Second, because of the reorganization of the host country's water resources planning structure, a niche for new techniques was available.

Third, the training of host country personnel and the systematization of contacts between MIT and Argentine professionals were both built into the program.

Fourth, the MIT team was a genuinely multidisciplinary team with interests in various aspects of water resources planning and with a sympathy for host country objectives.

Fifth, all of the models were constructed with host country computational capabilities in mind.

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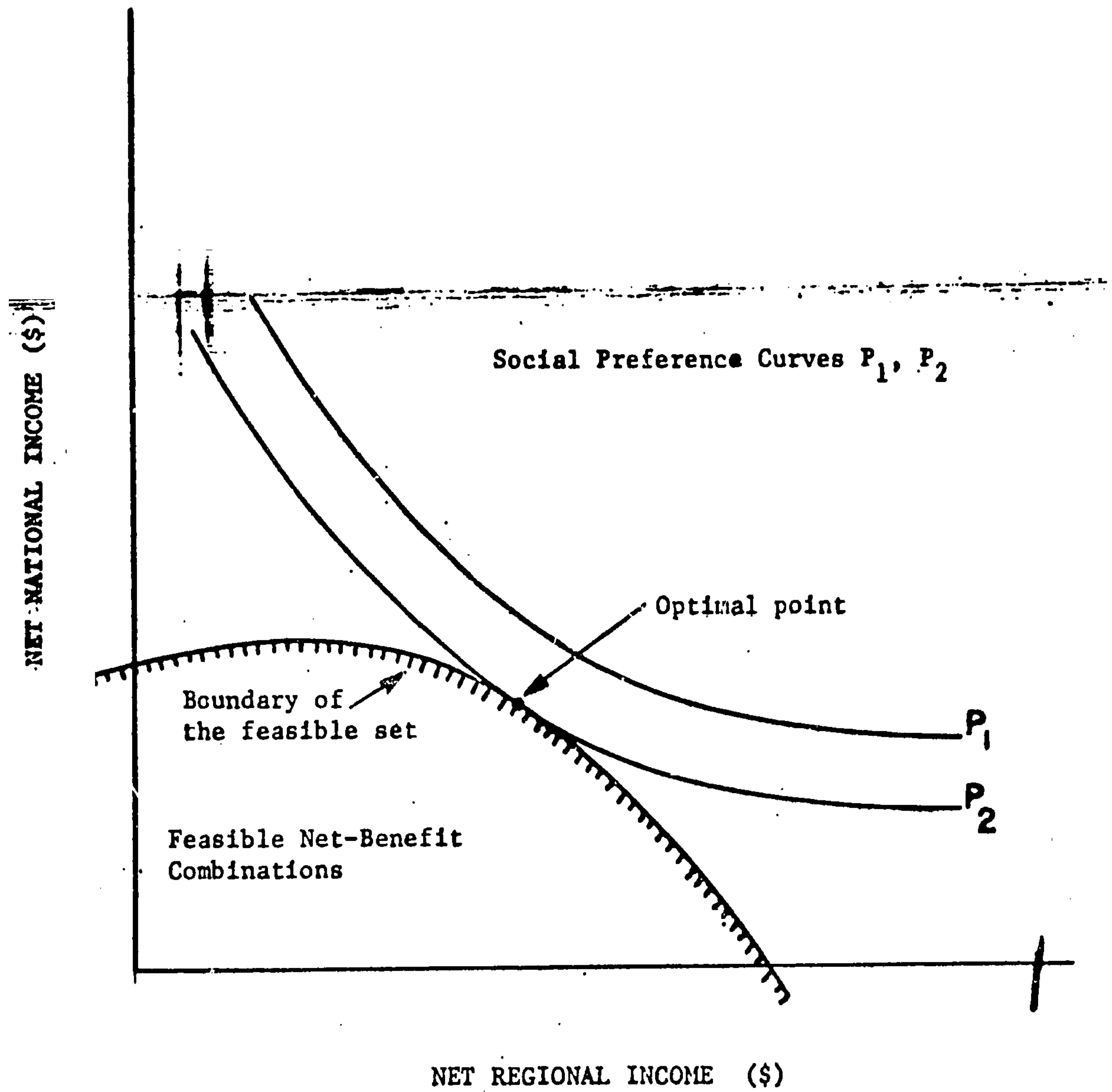

Figure 1 Graphical Presentation of Multiobjective Theory

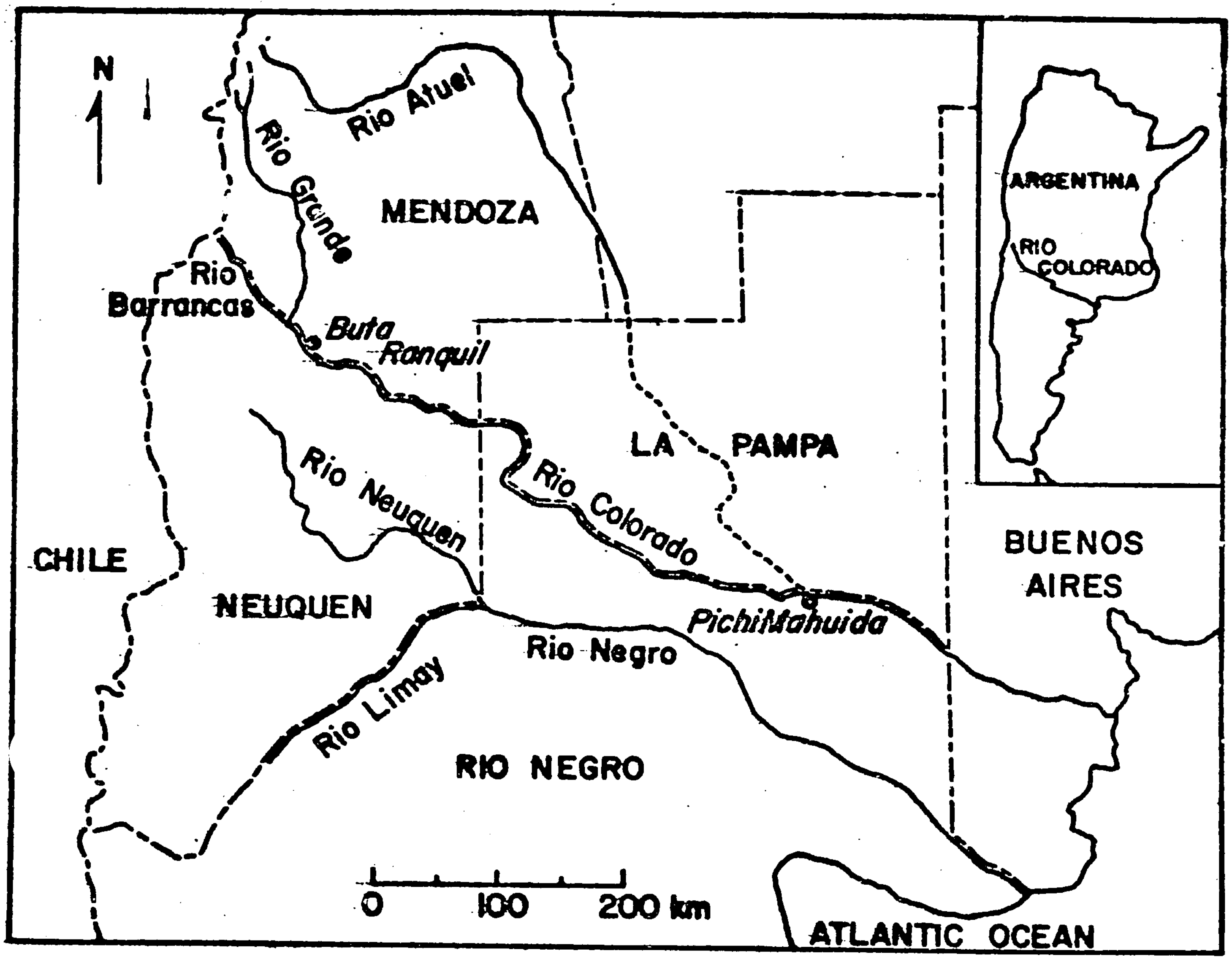

Figure 2: The Rio Colorado, Argentina