AGRICULTURE AND WATER QUALITY: NEW APPROACHES TO OLD PROBLEMS

EDWIN D. ONGLEY (*) - ARUMUGAM KANDIAH (**)

ABSTRACT

La contribution of agriculture to surface and groundwater water pollution in developed countries can be substantial and is well documented. In developing countries which typically have little control over municipal and industrial effluents, and have water quality data programs that are not capable of differentiating between different types of pollution sources, the relative role of agriculture in water pollution is not known. This has serious implications for agricultural planning, for national water resources policy formulation and implementation, and for national pollution abatement planning and investment. Decision-making, especially in data-poor environments, can now take advantage of new developments in: (1) water quality monitoring practices which, with institutional modernization of monitoring programmes, now make it possible to rethink and redesign data programmes that are more focused, practical, efficient, produce more information with less data; and (2) Information Technology (IT) that offer new and cost-effective means for enhancing the efficiency of decision-making both for on and off-site management issues and for agricultural planning and investment purposes. Examples are presented of new IT tools for agricultural use that can greatly assist in the cost-effective transfer of knowledge and experience from developed to developing countries.

RÉSUMÉ

La contribution de l'agriculture à la pollution de surface et souterraine dans les pays développés peut être remarquable et bien documentée. Dans les pays en voie de développement qui ont un faible contrôle des effluents ménagers et industriel, et qui ont des programmes sur les données de la qualité de l'eau qui ne réussissent pas à differencier entre les différentes sources de pollution, le rôle relatif de l'agriculture dans la pollution de l'eau n'est pas connu. Ceci a das implications sérieuses pour la planification agricole, au niveau de formulation et mise en application des politiques des ressources en eau nationales ainsi que pour la planification et les investissement pour le réduction de la pollution. La prise de décision, surtout dans les environnement qui ne disposent pas d'eau, peut à l'heure actuelle bénéficier des nouveaux développments dans: 1) les pratiques de monitorage de la qualité de l'eau qui, suite à la modernisation institutionelle des programes de monitorages, permettent aujourd'hui, de réfléchir et redessiner les programmes de données les plus intéressants, pratiques, efficaces et qui produisent plus d'information avec moins de données; et (2) la Technologie de l'Information qui offre de nouveaux moyens rentables pour améliorer l'efficience de la prise de décision, pour la gestion tant des problèmes sur le site qu'hors site et pour la planification agricole et les investissements. Ici on présente des exemples de nouveaux outils IT pour l'agriculture que peuvent être très utiles dans le transfer rentable de connaissance et d'exprériences des pays développés vers les pays en développement.

Freshwater is a finite and essential resource; it exercises a pervasive influence in all sectors of all societies, but most visibly in public health, food security, in economic and social development, and in environmental health.

Nevertheless, experts predict a global crisis in much of the developing world early in the 21st Century (United Nations, 1997) because of water scarcity and by loss of beneficial use from gross pollution in large parts of the world (Ongley & Kandiah, 1998). The United Nations projections to 2025 would require virtually all economically accessible water in the world to meet agricultural, industrial and household needs. Such a scenario is impossible in practice because of the inability to move available water to locations of demand (across and between continents, except as "virtual" water contained in food imports/exports) and because such projections assume efficient policy and administrative processes that optimize water use at national levels.

Less well known, especially at the level of national policy making, is the increasing linkage between water and national and global food security. Therefore, the implications for agriculture of a global freshwater crisis are especially serious.

Predicted population increase to the year 2025 and changes in dietary habits, especially in Asia, require an expansion of food production of about 40-45%. Globally, agriculture consumes some 70% of all available freshwater resources and more than 90% in some developing countries.

Projections of water requirements to meet food security to 2025 range from a 50-100% increase over current levels of water use. The implications for agriculture of water scarcity are likely to be most serious in south-east Asia (including China).

Demand for growth in food production has been met in the past by increasing land under agriculture, especially in irrigation agriculture, and by benefits of the "green revolution".

However, as effectively argued by Brown (1996), we have entered a period where availability of new land is limited, new water supplies are no longer economically available, groundwater aquifers are threatened by excessive drawdown (including seawater intrusion of important coastal aquifers) or by pollution, existing water is increasingly unavailable to agriculture due to competing demands by urban and industrial needs, and high levels of industrial pollution may make some water unsuitable for agriculture. Barring unforeseen developments in ge-

(*) Director, GEMS/Water Collaborating Centre, Canada Centre for Inland Canada.
(**) Senior Officer, Land and Water Development Division, Agriculture Division, Food & Agriculture Organization of the United Nations Rome, Italy.

netic engineering that increases productivity, Brown argues that the goal of food security may be difficult to attain in the long term.
Ongley and Kandiah (1998) summarized the major threats to water quality that are linked to food security as: (1) intensification of production both of rainfed and irrigation agriculture, and of aquaculture; (2) further expansion of rainfed agriculture into marginal lands that are highly susceptible to erosion; and (3) intensification of livestock raising, especially in Asia, to meet increasing demand for protein. These will be the consequence of political imperatives to produce more food, and will increase stress on water quality through intensified use of fertilizer and pesticides, the erosion of marginal lands that are pressed into service, the need to rehabilitate and put back into service irrigated lands that have been heavily salinized, and increasing discharges of animal wastes. Additionally, the agro-food processing industry is a significant and increasing source of organic pollution in many countries.
Especially in Asia where freshwater aquaculture is a major economic activity with important food and social implications, there is a need to balance food requirements against the degradation of freshwater systems that inhibits future beneficial use of the resource. Nevertheless, the ability to predict the future impacts of aquaculture as a pollution source, relative to the benefits of aquaculture as part of a remedial program in the restoration of eutrophic lakes, is poorly understood. Therefore, the ability to predict the net economic and environmental benefits or dis-benefits of aquaculture within a holistic management process for river/lake systems continues to elude planners and scientists.
In this paper we attempt to summarize recent work on the impacts of agriculture on water quality that was published by FAO (Ongley; 1996) and to draw on recent experience in the field of data programmes and in information technology that offer cost-effective solutions in the fields of agricultural planning and water quality impact assessment and minimization.

AGRICULTURE AND WATER QUALITY

Except for water lost through evapo-transpiration, agricultural water is recycled back to surface water and/or groundwater. However, agriculture is both cause and victim of water pollution. It is a cause through its discharge of chemical pollutants and sediment to surface and/or groundwater, through volatilization of ammonia which contributes to acidification of land and water, through net loss of soil by poor agricultural practices, and through salinization and waterlogging of irrigated land. It is a victim through use of wastewater and polluted surface and groundwater which contaminate crops and transmit disease to consumers and farm workers (Ongley, 1996). Agriculture exists within a symbiosis of land and water and, as FAO (1990) makes quite clear, "... *appropriate steps must be taken to ensure that agricultural activities do not adversely affect water quality so that subsequent uses of water for different purposes are not impaired*".
Relatively few countries attempt, or are able, to assess the relative role of agriculture in national water pollution inventories (Ongley, 1996; Ongley & Kandiah, 1998). In part this reflects the absence of relevant data, as noted below. In developed countries where there has been major emphasis on point source control the relative importance of agriculture in water pollution is high. In the United States the ranking of agriculture as a major polluter is noted in **table 1**. Fully 72% of assessed river length and 56% of assessed lakes are impacted by agriculture. These findings caused the US-EPA to declare that agriculture is the leading source of impairment in the Nation's rivers and lakes. Agriculture is also cited as a leading cause of groundwater pollution in the United States. In 1992, fully forty-nine of fifty states identified that nitrate was the principal groundwater contaminant, followed closely by the pesticide category. The US-EPA (1994) concluded that: "*more than 75% of the states reported that agricultural activities posed a significant threat to groundwater quality*".
Since the 1970's there has also been growing concern in Europe over increases in nitrogen, phosphorus and pesticide residues in surface and groundwater. Partly, this is a result of intense cultivation and "factory" livestock operations. Data on water pollution from agriculture in developing countries are more limited. According to various surveys in India and Africa, 20-50% of groundwater wells contain nitrate levels greater than 50 mg/l and in some cases as high as several hundred milligrams per litre (Convey and Pretty, 1988). In the developing countries, it is usually wells in villages or close to towns that contain the highest levels, suggesting that domestic excreta are the main source, though livestock wastes are particularly important in semi-arid areas where drinking water troughs are close to wells (Ongley and Kandiah, 1998).
Irrigation agriculture currently comprises 17% of all cultivated agricultural land yet produces nearly 40% of the world's food (United Nations, 1997). Irrespective of

Table 1 ***Leading sources of water quality impairment in the United States (¹).***

Rank	Rivers	Lakes	Estuaries
1	Agriculture	Agriculture	Municipal Point Sources
2	Municipal Point Sources	Urban Runoff/Storm Sewers	Urban Runoff/Storm Sewers
3	Urban Runoff/Storm	Hydrologic/Habita Modification	Agriculture
4	Resource Extraction	Municipal Point Sources	Industrial Point Sources
5	Industrial Point Sources	On-site Wastewater	Resource Extraction

(¹) From US-EPA, 1994.

availability of land for expansion of irrigation in the future, Alexandratos (1995) estimates that 2.5% of irrigated lands must be rehabilitated or taken out of production annually due to salinization and waterlogging. In addition to problems of waterlogging, desertification, salinization, erosion, etc., that affect irrigated areas, the problem of downstream degradation of water quality by salts, agrochemicals and toxic leachates is a serious environmental and public health problem.

Erosion and sedimentation

Amongst the range of anthropogenic activities, agriculture is one of the major producers of sediment. Unlike other major contributors of sediment such as construction activities that are usually intense but short-term in duration, sediment loss from agricultural surfaces is long-term and widespread. Pollution by sediment has two major dimensions (Ongley, 1996), both of which are central to off-site pollution assessment and control. There is the *Physical Dimension* which is top soil loss and land degradation by gullying and sheet erosion and which leads both to excessive levels of turbidity in receiving waters, and to off-site ecological and physical impacts from deposition in river and lake beds. There is a *Chemical Dimension* which is linked to the role of the silt and clay fraction (<631 ?? fraction) as a primary carrier of adsorbed chemicals, especially phosphorus, chlorinated pesticides and most metals, and which are transported by sediment into the aquatic system.

Because of the enormous implications of erosion and sediment loss in agriculture, agriculturalists world-wide have spent much time and resources attempting to find reliable methods of predicting erosion and sediment-associated chemical runoff under different conditions of crop type, tillage practices, etc. Consequently, there is a large number of models that have been developed for the prediction of agricultural non-point source runoff of sediment, nutrients and pesticides (summarized in Ongley, 1996). Many of the models permit gaming with alternative choices of land management, crop type, and fertilizer and pesticide application rates. There are three categories of models:

1. Simple *screening models*, such as the *unit load approach*, use published statistics on chemical and sediment runoff to provide approximate answers about the likely magnitude of sediment and chemical runoff. This approach is mainly focussed on impacts of agriculture on downstream water quality and without consideration of alternative farm management practices. Despite the unreliability and large margins of error this approach has been widely used as a cost-effective means for providing first-approximation answers for agricultural areas in the United States for which there are no data (McElroy, 1976; Mills *et al.* 1985).

2. Simple *empirical relationships*: the widely used and respected Universal Soil Loss Equation (USLE) of Wischmeier (1976) has had remarkable success at the plot level and has been incorporated into many of the mathematical models commonly used to simulate chemical transfer from agricultural surfaces. The USLE is designed as a field management tool and provides aggregated information at the storm, seasonal or annual level. Wischmeier (1976) reported that the average prediction error for annual soil loss was 12%; larger errors are to be expected for single storm events. The USLE is detailed here because of its success and because the same type of approach has been used in Africa (Elwell & Stocking, 1982) and elsewhere (e.g. FAO, 1985, 1986, 1991; Modified USLE in Brazil by Chaves, 1991). This methodology is also used in the AgriScreen "advisor" that is described below.

The USLE is calculated as: A = R. K. LS. C. P

where:

A = Calculated soil loss in tonnes ha^{-1} for a given storm or period.

R = Rainfall energy factor

K = Soil erodibility factor

LS = Slope-length factor

C = Cropping management factor (vegetative cover)

P = Erosion-control practice factor

Each of the factors can be calculated or estimated using field data (as in the case for R and LS) and from tables or nomograms for all other factors. Novotny and Olem (1994) provide an excellent commentary on this and other methods for estimating or modelling erosion. The USLE is designed for rainfall only and does not handle snowmelt or rainfall on frozen ground. The USLE requires calibration data from standard plot experiments which are widely available in North America and, more limitedly, from other parts of the world.

Although Wischmeier (1976) has cautioned against extending soil loss models beyond field loss studies, these models are intuitively attractive for predicting erosion over large areas. It should be noted that, due to transport losses (generalized as the Sediment Delivery Ratio), such erosion estimates apply only to total erosion at source and do not reflect sediment loads (or sediment yield) measured at downstream locations. Such estimating techniques would, if calibrated so that the errors are known, have useful application as a screening tool for the estimation of erosion potential under conditions of similar crop, soil and topographic factors over large areas. Internationally, there appears to be little systematic information on calibration; however the Network on Erosion-Induced Loss in Soil Productivity (FAO, 1991) may eventually provide suitable information.

3. There is a wide variety of *deterministic and stochastic models* that attempt to simulate the physics of the erosion process. The data requirements for calibration and verification are extremely large. While such models may have certain advantages, especially in terms of the

level of detail in which one can simulate alternative farm practices, these are generally unsuitable for developing countries due to their data requirements and the observation that management judgements for farm-level decisions can almost always be made on the basis of more generalized data combined with experience and common sense.

SELECTED PROBLEMS AND PROPOSED SOLUTIONS

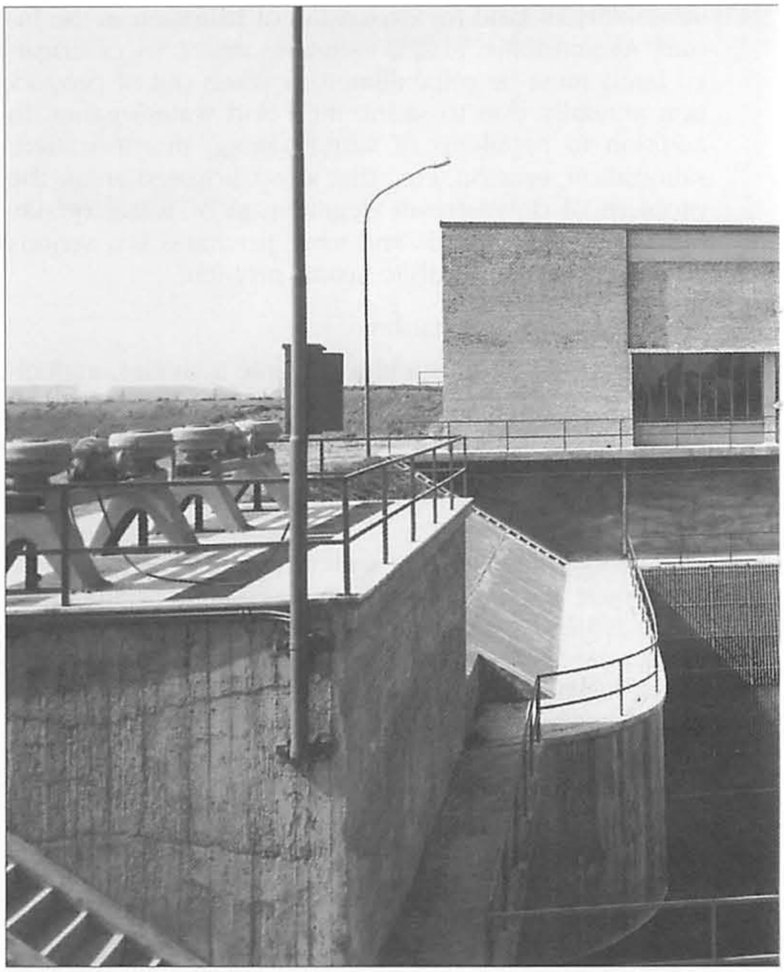
The challenge to governments will be to integrate agricultural decision-making into the larger policy decisions involving national or basin-wide freshwater quantity and quality management. This would include agriculture within the larger pollution remediation context so that remediation investment is targeted towards optimal solutions that discriminate between pollution loadings of point and nonpoint sources, their control options, and relative effectiveness and efficiency of alternative control strategies. Here we address some specific issues involving agricultural planning, management, and water data programs, that require urgent attention and for which there are novel solutions that merit attention.

1. Water quality data programmes

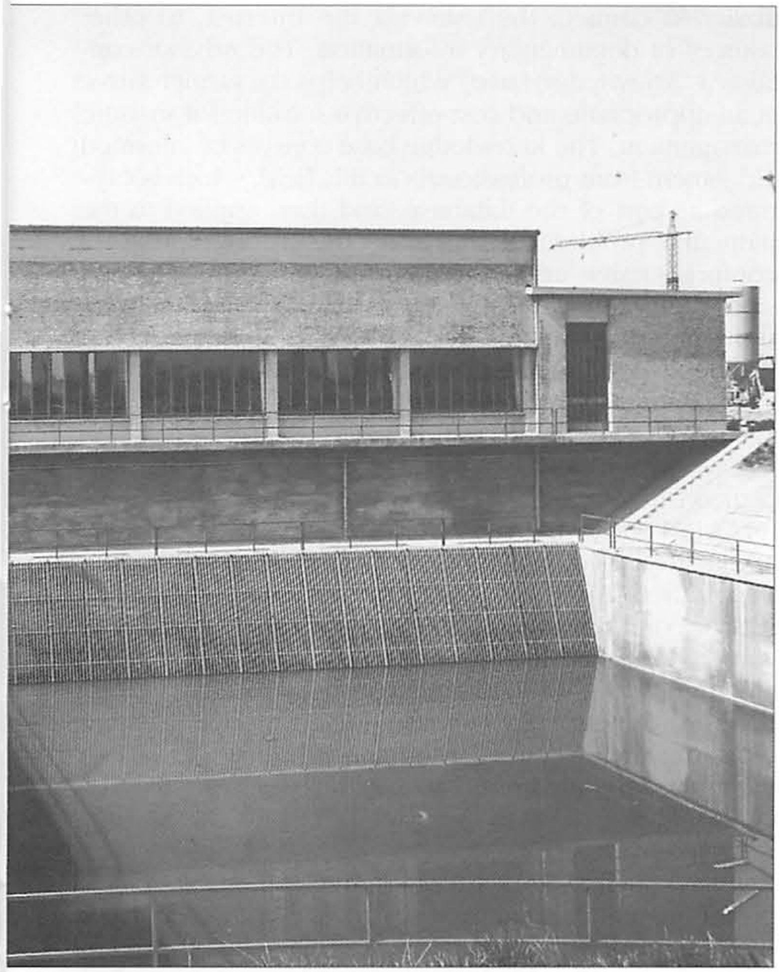
The data problem was summarized by Ongley (1994) at the 1993 Stockholm Water Symposium as: "... a common observation amongst water quality professionals is that many water quality programmes, especially in developing countries, collect the wrong parameters, from the wrong places, using the wrong substrates and at inappropriate sampling frequencies, and produce data that are often quite unreliable; the data are not assessed or evaluated, and are not sufficiently connected to realistic and meaningful programme, legal or management objectives. This is not the fault of developing countries; more often it results from inappropriate technology transfer and an assumption by recipients and donors that the data paradigm promoted by developed countries is appropriate in developing countries." More recently the United Nations (1997) referred to a "data crisis" in their efforts to carry out a comprehensive global assessment of freshwater quality and quantity. A similar observation has been made by UNIDO (1996) in their attempt to forecast pollution factors.

The reason for this situation has institutional, legal and technical roots which are too complex to review here in detail (Ongley, 1997). Nevertheless, the data crisis is being flagged in several fora as a national catastrophe at a time when countries need reliable information upon which to make cost-effective investment decisions on remediation and development in the water sector. Within the framework of national pollution abatement planning and investment programs the impact of the data crisis on agriculture can be summarize as (Ongley and Kandiah, 1998):

1. Serious widespread degradation of water resources that can be primarily attributed to agriculture, as in nitrate pollution of groundwater, may go unrecognized;
2. Spatially limited downstream pollution from small-scale agricultural practices such as animal-raising are not recognized yet may have severe public health consequences;
3. The presumption of widespread pollution from agricultural practices may not be warranted relative to other contributors of nutrients, sediment, and toxic substances;
4. Prediction of downstream pollution for new agricultural development schemes (e.g. irrigation expansion) is not possible, and
5. Investment decision-making for point or nonpoint pollution control is unable to assess the cost-benefit of different pollution abatement options.



Significant for agricultural programs is that water quality data are rarely collected by ministries of agriculture yet these same ministries often have jurisdiction over rural water supply. Sustainable agriculture within the framework of comprehensive basin management will require relevant and reliable data upon which to make management decisions. This may necessitate intervention by agriculturalists in existing water quality data



programs if relevant data are to be collected for agricultural management and rural water supply purposes.

2. Use of new information technologies for decision-making in agriculture

An often cited benefit of Information Technology (IT) is the ability to electronically access data, text, graphics, etc. from an infinite number of locations in the world. The hardware and software (e.g. World Wide Web on the Internet) is now reliably dedicated to such tasks to the point where information overload is now a problem. Nevertheless, while this type of IT is the best known aspect of the information revolution, it is only one side of the IT equation. The second side deals with the problems created by this ease of access —specifically, the immense problem of what to do with such large amounts of information when it is received and how to use it for decision purposes. Indeed, the challenge is no longer that of accessing information but one of integrating information in a systematic manner for the purpose of making management judgements about particular projects and problems in agriculture in general, and the management of water quality in particular. Part of the historical problem of environmental management and, more specifically, of agricultural planning and management, has been the difficulty of cost-effectively transferring knowledge and experience from developed countries to developing countries, or from one developing country to another. Generally, technology transfer has been in the form of: "consultants"; capacity building (including in-country and foreign training); published guidelines; information clearinghouses (which now-a-days are Web-based), and turn-key installations (installs capacity but usually adds little to domestic expertise). New developments in the field of Information Technology (IT), however, have the potential to revolutionize the transfer of domain knowledge (i.e. experience in a particular field). Moreover, the incorporation of knowledge bases (as opposed to databases) into PC-based decision-support software designed around particular problems can bring a wealth of experience into the hands of non-expert users in an easy-to-use manner.

In agriculture, as in other fields, innovative use of IT technology within decision-support applications has enormous potential. Published guidelines represent cumulative knowledge in fields such as wastewater use in agriculture, optimizing water use in irrigation, and scoping probable impacts of agricultural projects on water quality, to name but three examples. However, guidelines are seriously limited by:

— space and cost limitation of printed guidelines.

— cost of frequent up-dating and printing of guidelines.

— inability to incorporate the complexity of real-world situations into printed guidelines.

— difficulty in circulating printed guidelines to potential users.

The following are three examples that represent a type of IT software application commonly called electronic "Advisors". Advisors focus on a specific type of problem, are relative inexpensive to build, and can be easily up-dated and circulated via the Web or on diskette. The User is presented only with the information that applies to his particular situation but is offered the option of additional information. In assisting the User to reach a decision, the Advisor can be designed to so that the User is presented with options, and is informed of the degree of confidence placed on the identified options. Advisors can range from simple situations up to programmes which use the full range of information technologies such as Expert Systems (knowledge base), neural networks (self-learning), fuzzy logic (uncertainty), etc. and which are increasingly being used in complex decision-support software. While these advanced technologies are invisible to the User they often permit analysis of uncertainty in the decision process which can be very beneficial to the User.

(a) EXPRES

The EXpert system for Pesticide Regulatory Evaluations and Simulations (EXPRES) is a self-contained software programme which permits the user to explore the potential for contamination of shallow groundwater by pesticides through the use of models and pesticide databases that are built into the software (Crowe and Mutch, 1994). Ordinarily, assessment of potential for contamination of shallow ground water by agricultural pesticide applications is expensive, requiring extensive site information including vertical geophysical data obtained through coring, and subsequent modelling. There was a need to develop a screening technique that would allow non-experts to estimate the potential for groundwater contamination without the expense of drilling wells, making detailed field and laboratory measurements, hiring consultants, etc.

The EXPRES expert system consists of a "knowledge base" (informed judgement by experts in this field and which is captured as part of the database, a database of pesticide and other relevant information, and three pesticide assessment models. Using the User's available data and study objectives, EXPRES selects the most appropriate model, assists the user in construction of an input data set, initiates the assessment, and aids in the interpretation of the results. EXPRES can review pesticide and site properties, assess the potential for leaching to groundwater relative to other possible pesticides, make quantitative predictions on the distribution and migration rates of the pesticide, and evaluate the processes and factors that control the fate of pesticides in the subsurface.

EXPRES has been expanded into a regional assessment tool by Crowe and Booty (1995) with three different scales of application —soil profile scale, local scale, and regional scale. The most detailed analysis is at the soil profile scale, whereas the larger scales are used as screening tools by regulators to determine the relative potentials for groundwater contamination and the need for groundwater monitoring.

(b) Manure Wizard

Manure management at the farm level is mainly driven by problems of water quality impacts. Manure management is often complex, involving decisions about manure chemistry, animal types, quantitative prediction, economics of manure handling, different options for disposal, spreading on land under different conditions of soil, slope and crop types, etc. Because manure management has significant pollution potential as well as significant costs at the farm level for containment and disposal, the *Manure Wizard* provides the farmer with as much information as is needed to make an informed decision about his options. This Advisor, developed at the University Guelph (Canada) for Agriculture Canada allows the farmer to interrogate the information system about any aspect of manure management under different types of agricultural conditions that are found in Ontario. The system contains relevant text as well as the ability to connect the user, via the Internet, to other sources of documentary information. The Advisor contains a "knowledge base" which helps the farmer arrive at an appropriate and cost-effective solution for manure management. The knowledge base consists of informed judgement from professionals in this field, which is captured as part of the database, and then applied to the particular problem of the user. The Advisor provides comprehensive and systematic information for decision- making to the farmer, and requires no computer skills on the part of the User. Each computer screen leads the User through a series of questions and provides guidance on those issues relevant to manure management. Using "hypertext" linkages, the user can interrogate specific words, titles, phrases or issues that appear on the screen. Hypertext then immediately transfers the User to the relevant section of the Advisor or automatically connects the user to an external information source. Advisors tend to be designed for specific sets of conditions. Both *EXPRES* and the *Manure Wizard* are designed for application under humid temperate conditions and agricultural systems found in Canada; nevertheless, they can be adapted to include other types of climatic and agricultural conditions. Both these examples are illustrated in greater detail in Ongley (1996).

(c) AgriScreen

Agencies such as FAO are often involved in assisting or promoting agricultural projects in developing countries. Increasingly there is requirement to evaluate off-site impacts. Ordinarily, this is carried out by collecting data (expensive) and running simulation models. Although there are much data on downstream impacts in developed countries, hard data are rare in developing countries where the development scenarios for food security are likely to be implemented. There are also problems of reliability due to absence of reference studies or other means of verification of predicted impacts. Further, traditional modelling approach is too expensive and not especially useful for screening purposes. Using experience from other areas together with accessible site information, an electronic advisor makes it possible to forecast the range of probable impacts on downstream water quality for the existing physical conditions and the anticipated crop and crop management conditions. This makes it possible to "game" with alternative crop and management options in order to develop an appropriate balance between economic output, implementing and operating costs, and off-site pollutant loadings.

The Agricultural Project Screening advisor (**table 2**), now being developed in prototype for FAO, is designed to provide a screening-level capability to predict the probable range of off-site pollutants from proposed new projects for dryland or irrigated agriculture. The methodology uses the Universal Soil Loss Equation pa-

Table 2 ***Components of the*** **AgriScreen** ***Advisor.***

Case library ⇓	Screening Level	⇓ Planning Level
"Knowledge base" based on real cases of combinations of climate, soil, landscape, crop, management, etc Requires Case Librarian.	Input field characteristics per template. Where site data are unknown can access electronic information sources such as world soil, climate maps or databases.	Runs AGNPS or other models, prompting re data needs, output reliability, etc.
	Attempts to match field situation with one or more cases in the case library.	
	Allows interrogation of cases for pertinent metadata. *Planned Outputs:* High/Medium/Low values for: — Erosion and sediment output. — Nutrients - N,P,K — Pesticides — Salinity Measure of reliability given.	

rameters insofar as these form the basis for most agricultural models that deal with chemical runoff. A similar expert rule-approach for erosion estimation in the United Kingdom was presented by Harris and Boardman (1990). The objective is, initially, to develop a "case library" of water quality outputs that have been observed and published in the primary or grey literature for a selection of crop, management, soil, landscape and climatic variables. Recognizing that these published examples are unlikely to cover terrain and crop types in many developing countries, the case library is expanded through the addition of case histories based on the experience of agricultural professionals in developing countries. For any proposed agricultural project the planner fills a template with available physical, climatic and agronomic information.

The Advisor predicts the probable range of pollutant outputs by matching the input information against the case library, the uncertainty associated with cases used for the prediction, and makes available pertinent metadata so that the User can evaluate the adequacy of the prediction for his particular situation. This approach can also be used at a more detailed planning level (**table 2**) where the screening component advises which types of parameters are most likely to be a problem under different conditions of agricultural practice. Any subsequent investigation can then focus only on the problem component. ●

REFERENCES

Alexandratos N. (Ed.) (1995) - World Agriculture Towards 2010: An FAO Study. FAO, Rome.

Brown L.R. (1996) - Tough Choices: Facing the Challenge of Food Scarcity. The Worldwatch Environmental Alert Series, Norton & Company, New York.

Chaves H.M.L. (1991) - Análise global de sensibilidade dos parâmetros da equaçao universal de perda de solo modificada (MUSLE). R. bras. Ci. Solo, Campinas, 15: 345-350.

Convey G.R. and Pretty J.N. (1988) - Fertilizer risks in the developing countries: a review. International Institute for Environment and Development, London.

Crowe A.S. and Booty W.G. (1995) - A multi-level assessment methodology for determining the potential for groundwater contamination by pesticides. Environ. Monit. Assess. 35: 239-261.

Crowe A.S. and Mutch J.P. (1994) - An expert systems approach for assessing the potential for pesticide contamination of ground water. Ground Water 32: 487-498.

Elwell H.A. and Stocking M.A. (1982) - Developing a simple yet practical method of soil loss estimation. Tropical Agriculture (Trinidad) 59: 43-48.

Fao (1985) - Erosion-Induced Loss in Soil Productivity: A Research Design. Stocking, M., Consultants Working Paper No. 2, Soil Conservation Programme, Land and Water Development Division, Food and Agriculture Organization of the United Nations (FAO), Rome.

Fao (1986) - The cost of soil erosion in Zimbabwe in terms of the loss of three major nutrients. Stocking M., Consultant's Working Paper No. 3, Soil Conservation Programme, Land and Water Development Division, FAO, Rome.

Fao (1990) - Water and sustainable agricultural development: A strategy for the implementation of the Mar del Plata Action Plan for the 1990's. FAO, Rome.

Fao (1991) - Network on erosion-induced loss in soil productivity. Report of a Workshop, Bogor, Indonesia, March 1991. Land and Water Development Division, FAO, Rome.

Harris T. and Boardman J. (1990) - A rule-based expert system approach to predicting waterborne soil erosion. In Boardman, J., Foster I.D.L., and Dearing, J.A. (Eds.) Soil Erosion on Agricultural Land. John Wiley & Sons Ltd., London.

Mcelroy A.D., Chiu A.D., Nebgen S.Y., Aleti J.E., and Bennett F.W. (1976) - Loading Functions for Assessment of Water Pollution from Nonpoint Sources. EPA-600/2-76-151, U.S. Environmental Protection Agency, Washington, D.C.

Mills W.B. et al. (1985) - Water Quality Assessment: A Screening Procedure for Toxic and Conventional Pollutants, EPA-600/6-82-004a & b, Volumes I and II. U.S. Environmental Protection Agency, Washington, D.C.

Novotny V., and Olem H. (1994) - Water Quality: Prevention, Identification, and Management of Diffuse Pollution. Van Nostrand Reinhold, New York.

Ongley E.D. (1994) - Global water pollution: challenges and opportunities. Proceedings: Integrated Measures to Overcome Barriers to Minimizing Harmful Fluxes from Land to Water. Publication No. 3, Stockholm Water Symposium, Aug. 10-14, 1993., Stockholm, Sweden, pp. 23-30.

Ongley E.D. (1996) - Control of Water Pollution from Agriculture. FAO Irrigation and Drainage Paper No. 55. FAO, Rome.

Ongley E.D. (1997) - Matching Water Quality Programs to Management Needs in Developing Countries: The Challenge of Program Modernization. European Water Pollution Control, (in press).

Ongley E.D. and Kandiah A. (1998) - Managing water pollution from agriculture in a water scarce future. Proceedings of the 1997 Stockholm Water Symposium, August 11-14, 1997. (in press).

United Nations (1997) - Comprehensive Assessment of the Freshwater Resources of the World. Report of the Secretary General. Commission on Sustainable Development, 5th Session, 7-25 April 1997. Document E/CN. 17/1997/9.

US-EPA (1994) - National Water Quality Inventory. 1992 Report to Congress. EPA-841-R-94-001, Office of Water, Washington, DC.

Wischmeier W.H. (1976) - Use and misuse of the universal soil loss equation. J. Soil Water Conserv. 31, 5-9.