An aquatic macroinvertebrate and chemical database for riverine ecosystems

Dallas HF[1]*, Janssens MP[2] and Day JA[1]
[1] *Freshwater Research Unit, Department of Zoology, University of Cape Town, Private Bag Rondebosch 7700, South Africa*
[2] *Soft Craft Systems cc, PO Box 30169, Tokai 7966, South Africa*

Abstract

A database has been developed comprising biological (macroinvertebrate) and chemical data derived from documented studies of riverine ecosystems within South Africa. The intrinsic variability of biotic and chemical components of these ecosystems has necessitated the adoption of a three-level hierarchical framework within which the biological and chemical data are accessed and queried. The primary level is the regional or geographic framework and includes water quality management regions, bioregions and political regions; the secondary level differentiates longitudinal components or subregions and the tertiary level is the site. Biological data, as percentage abundance, are given for each biotope sampled. The associated chemical data, standardised into SI units, are given for each site. The South African Scoring System (SASS), which is a rapid bioassessment method used to detect water quality impairment in riverine ecosystems, has also been incorporated to enable an estimate of water quality impairment to be established based on historical data. An outline of the querying frameworks is given and uses and potential problems of the database are discussed.

Introduction

Research on the ecological aspects of rivers in South Africa began in the early 1950s (e.g. Harrison and Elsworth, 1958; Scott, 1958) and was followed by a number of studies in the 60s (e.g. Allanson 1961; Harrison and Agnew, 1962; Chutter, 1963; Hughes, 1966; Chutter, 1967; Brand et al., 1967; Allanson, 1968; Forbes, 1968; Archibald et al., 1969), 70s (e.g. Kemp et al., 1976; Coetzer, 1978; Fowles et al., 1979), 80s (e.g. Fowles, 1984a; 1984b; O'Keeffe, 1985; Coetzer, 1986) and 90s (e.g. Palmer and O'Keeffe 1990; Brown, 1993; King and Tharme, 1994; Dallas, 1995). Many recent studies utilise historical data from earlier studies which enable comparisons of biological and/or chemical data between current and historical conditions to be made and the degree of change, in for example, water quality, to be ascertained. Availability and accessibility of documented studies are often problematic since much of the early work was published in reports that are presently not readily available.

The compilation and development of the aquatic macroinvertebrate and chemical database (BioBase) have taken place over the last five years. Initially, the intention was to utilise these data to assist in the construction of water quality rating curves for use by the Department of Water Affairs and Forestry (DWAF). Subsequently this objective became inappropriate and it became clear that the development of a database derived from biological (macroinvertebrate) data and which included relevant chemical and physical parameters of the associated water body, would provide useful information for ascertaining the characteristics of water bodies with respect to both biota and water chemistry. Subsequent advances in associated projects and the initiation of the national biomonitoring programme for riverine ecosystems reinforced the potential usefulness of such a database, and led to a number of other features such as incorporation of spatial scales (e.g. bioregions, water quality management regions, subregions etc.) and data related to SASS (South African Scoring System). One of the most important aspects of the database is that it enables the linking of biological and chemical variables on both spatial (data collected from the same place) and temporal (data collected at the same time) planes.

Sources of data

The database has been constructed using data pertaining to South African rivers and extracted from most of the available literature and unpublished reports, in which biological and chemical data were collected concurrently (**Appendix 1**). Most of the biological data that are available relate to the benthic invertebrate fauna, although some work has been done on fish. This bias is probably a result of the early recognition of the fact that the benthic fauna provides an easy and fairly reliable way of assessing pollution (Chutter, 1972). Records of the invertebrate riverine fauna thus form the biological component of this database. These data include those from intensive studies of individual systems (e.g. Harrison and Elsworth, 1958; Chutter, 1963; 1967), extensive one-off surveys of regions (e.g. Kemp et al., 1976), *ad hoc* surveys (e.g. Harrison and Agnew, 1960; 1962) and impact assessment reports (e.g. O'Keeffe, 1987; 1989). Thus far 43 studies, of which 40 had associated chemical data, have contributed to the biological records of the database. It is intended that updating of the records from fresh sources will be an ongoing exercise. Details of the history and source information for the database have been previously documented (Dallas et al., 1995; 1998).

The chemical data were extracted from the same literature sources as the biological data, but vary between studies in terms of the number of variables analysed. The main criteria for the inclusion of chemical data have been the exact or approximate coincidence of these measurements with those of the relevant invertebrate biological details. Suffice it to say that a total of 140 000 biological records have been entered into the database thus far, and most are accompanied by records of chemical conditions (between 1 and 48 chemical variables covered in each

* To whom all correspondence should be addressed.
☎ (021) 650-3603; fax(021) 650-3301; e-mail hdallas@botzoo.uct.ac.za
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case) in the river at the time of sampling.

This paper aims to provide an overview of the database with attention paid to its structure and potential utility. More detailed information on the utilisation of the database is documented in a user manual (Dallas and Janssens, 1998), which introduces the user to the database structure, outlines the types of queries that can be executed and specifies the technical information. There is always a danger that a large store of data such as this may exude an air of reliability by virtue of its size alone. It is important to understand and be aware of the problems involved in amalgamating records from different sources, relating to data gathered by different authors, at different levels of intensity, and for different purposes. These problems are expanded on in the discussion of the structure and potential utility of the database.

Hardware and software requirements

The database has been created using Microsoft Access.97, which is a relational database operating on IBM-compatible PCs in the Windows environment. Querying has been streamlined using Microsoft Excel (97 SR-1). Data are easily exported for further analysis in statistical packages such as Statistica or in geographical information systems (GIS) such as PC-ArcView, since all sites have latitude and longitude co-ordinates associated with them. At least a 486 PC with a minimum of 16 MB RAM is required to run the database, although the system works much more efficiently on a Pentium 133 or higher with 32 MB RAM. The database is supplied on CD as a run-time version of Microsoft Access, but requires Microsoft Excel.97 (for Access Version.97). Copies of the CD and user manual are available from the Water Research Commission.

Structure of the database

The intrinsic variability of biotic (Harrison and Agnew, 1962; Eekhout et al., 1997) and chemical (Day and King, 1994) components of riverine ecosystems within South Africa has necessitated the adoption of a hierarchical framework within which biological and chemical data are accessed and queried. The primary level is the regional or geographic framework, the secondary level is at the longitudinal differentiation and the tertiary level is the site. The hierarchical relationship between each level is schematically indicated in Fig. 1. Current initiatives aimed at refining river classification (e.g. National Biomonitoring Programme, Ecological Reserve Programme) should provide additional information which could be incorporated into the database at a later stage.

Primary level: Geographic frameworks

Three frameworks have been incorporated at this level to allow for selection of sites and hence biological and chemical data within the regions defined below.

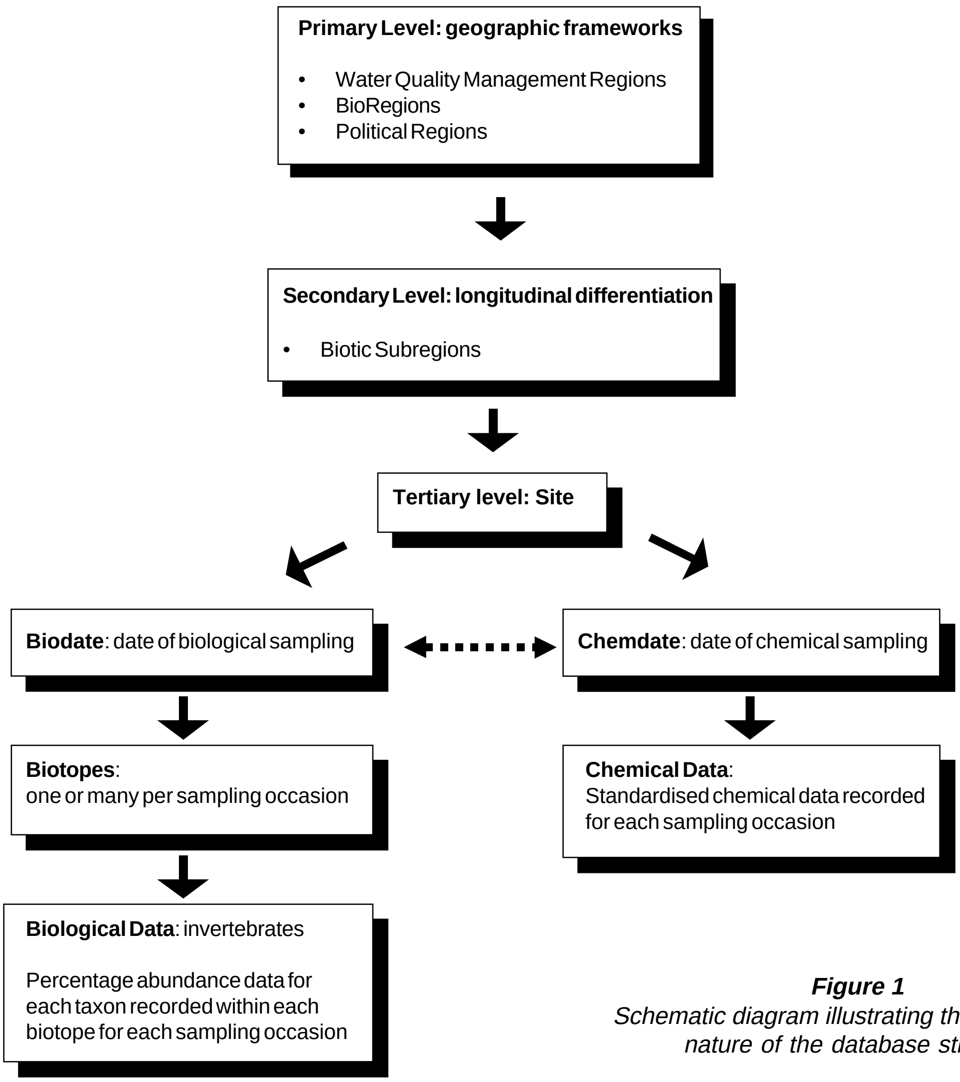

Figure 1
Schematic diagram illustrating the hierarchical nature of the database structure

- Water quality management regions which are based on DWAF water chemistry data, were proposed at a secondary catchment level (Day et al., 1999). These have been refined using new information such as bioregions.
- Bioregions (Brown et al., 1996) are a refinement of the biogeographic regions, which were based on broad historical distribution patterns of riverine macroinvertebrates, fish and riparian vegetation (Eekhout et al., 1997).
- Political regions within South Africa were deemed important because riverine ecosystems are often managed within provincial boundaries.

Secondary level: Longitudinal differentiation *(Subregion)*

In addition to the above geographic frameworks, it was considered important to incorporate a measure which takes account of the longitudinal zonation of rivers (Harrison, 1965; King, 1981). The subregional classification developed at the spatial framework workshop (Brown et al., 1996), and which reflects broad geomorphological characteristics and distribution patterns of components of the biota, was used as a template. For example rivers in the Fynbos Bioregion have been divided into four subregions: namely Mountain Stream, Foothill, Transitional and Lowland. In some instances additional subregions have been incorporated. The Level 3 classification proposed at the workshop (Brown et al., 1996), i.e. River Types, was not incorporated since it is still in the development phase. It would, however, be advantageous to incorporate information related to this level as it becomes available.

Tertiary level: Site

The site is the level at which the biological and chemical data are collected and thus far data are available for 684 sites on 205 rivers within South Africa. Associated with each site is information on the spatial location of the site, including a description of the site and details of the river, subregion, bioregion, political region, water quality region, latitude, longitude and altitude of the site. Biological and chemical data for each site are linked to the site in a hierarchical manner as illustrated in Fig. 1.

Biological data

Biological data are given as percentage abundances, for each biotope (e.g. stones-in-current, marginal vegetation) sampled, for each sampling occasion. Biotopes are at the level at which the biological information was collected. Variability in both terminology and methodology between studies necessitated the adoption of a hierarchical structure (i.e. broad biotope, specific biotope and substratum) in order to take into account the numerous biotopes sampled. Each biotope is also assigned a SASS biotope (Chutter, 1995) which provides a more uniform basis from which comparisons can be made. Details of the hierarchical arrangement of the biotope categories are given in Dallas et al. (1998).

The presence or absence of each taxon has been included in a yes/no manner, and when present the abundance of the taxon is expressed as a percentage occurrence because of the semi-quantitative nature of much of the data. Abundances given as "p" in the original study text, indicating that a taxon was present in a very low abundance, are reported as abundance=0.01. Absent taxa are those not recorded at particular sites or at particular time periods within a study reference. The taxonomic level, i.e. order, family, genus, species etc., documented in the study is given whereby each unique taxon is allocated a unique, numerical code. Thus far 1902 unique taxa have been specified. The state of flux of the taxonomy and inconsistent historic record of species names are to be noted, and caution is advised when querying on the lower taxonomic levels (e.g. species). Synonymous names and all taxonomic levels have been incorporated when known, although continuous modifications are likely to occur with respect to both synonymy and taxonomy.

SASS summary data

SASS is a rapid bioassessment method, based on the sensitivity/tolerance of macroinvertebrates to water quality impairment. It is designed to assist in the detection and monitoring of water quality in riverine ecosystems. Application of SASS scores to historical data in the database provides a crude means of ranking or ascertaining the extent of water quality impairment at each site. It is limited in that certain studies were restricted to a single biotope whilst others incorporated numerous biotopes considered collectively. Certain data are the result of a single sampling occasion whilst others are more intensive and the combination of months and/or years. These aspects need to be taken into consideration if SASS summary information is used. Each distinct SASS taxon as matched from the identified taxa recorded for each sampling occasion is used to calculate SASS4 score, number of taxa and ASPT for the site. The number of SASS biotopes, i.e. stones-in-current, stones-out-of-current, marginal vegetation, aquatic vegetation, gravel, sand and mud, are also calculated for each sampling occasion.

Chemical data

Chemical data were recorded in 40 of the 43 studies documented in this database. The variables measured and units reported varied between studies. These units have been standardised into SI units where possible, and conversions made where applicable. A full list of the chemical variables for which we have records is given in Dallas et al. (1995).

Biodates and chemdates

"Biodate" and "Chemdate" refer to the periods in which biological and chemical data were collected respectively. Sampling frequency was highly variable, with some records being one-off "spot" samples, while others are the means of weekly, monthly, seasonal or annual samples. The presentation of data in reports and published papers is also highly variable, with results being presented either as one-off samples with different degrees of detail as to day, month and year of sampling, or as monthly, seasonal or yearly means. In some cases, results are of monthly or seasonal data, presented as a mean over a few years (although data that have been used in this database never span more than three years). To facilitate querying the bio- and chemdates have been standardised (Year.Month.Day) and "Sort Month", "Sort Year" and "Sort Season" allocated to each. To allow this, some dating conventions, detailed in Dallas et al. (1998), have had to be established. As with all conventions, these should be regarded with caution, since while they render accessing of data more convenient, they also decrease the accuracy with which those data are presented. Some inaccuracies are inherent to such a hierarchical system and to counteract this to some degree, warning codes have been added which describe the type of sampling on which the data are based. The data include: "Spot Sample Data" which are data from one-off surveys; "Month Pool Data" which are data collected seasonally and for which "Sort Month" is deduced by convention; "Year Pool Data" which are data taken in the same month and presented together as a mean over several years; and "Both Pool" which are data for which both month and year sort dates are artificial and records are presented as seasonal means, over a number of years.

Linking biological and chemical data

One of the reasons for the development of this database was to facilitate a linking of biological and chemical data. Whilst acknowledging that there are inherent problems in doing this, there is sufficient utility in such a function. For example, one is able to ascertain the range of pHs at which a particular species or family has been recorded. It was therefore necessary to link the biological and chemical data. Problems arose due to the inconsistent nature in which the data were reported, especially with respect to the temporal references, making it impossible to link the data in a straightforward manner. To overcome this problem, the sampling dates from each study have been assessed, and a subjective judgment made as to the best matched chemical and biological data, for each site. When biological and chemical samples were taken at the same time, however, matching was straightforward. Specific rules are applied to the linking process, details of which are given in Dallas et al. (1998). A conservative attitude was adopted for the linking of these data sets, so that not all the biological data stored in the database have been linked to chemical data, and *vice versa*.

Study references

The author, year, title and journal details are given for each study which is numerically coded and used to reference both the biological and chemical data.

Querying the data

The database has been designed to facilitate querying in a manner that only requires a basic knowledge of Microsoft Access and Excel. The Query Centre has three pre-defined query frameworks whereby biological or chemical data may be queried independently or in combination. Within each framework it is possible to select taxonomy level (phylum, class, order, family, genus species etc.), chemical parameter(s), biotope (SASS, broad, specific, substratum, description), region (bioregion, water quality region, political region), subregion, river and site(s), date (year, month, season, warning), study reference and/or SASS criteria (SASS4 Scores, number of taxa, ASPT or number of SASS biotopes) as appropriate. Detailed descriptions of each query framework are given in the manual (Dallas and Janssens, 1998) and examples of the results are illustrated and discussed.

Uses and potential problems of the database

Deducing ranges of different water quality variables, for different taxa

Deducing ranges of different water quality variables, for different taxa, was the purpose for which the database was originally designed. We hoped that, by means of correlation analyses, we would be able to draw conclusions about the biogeographical ranges of different taxa, relative to water quality variables. Inadequacies in the data, such as uneven temporal and geographic coverage, problems of incompatibility of some measurements, and a lack of consistency in the range and thoroughness of chemical measurements, meant, however, that any reliable correlation analyses were unlikely to be forthcoming. Assisting with the production of water quality guidelines for aquatic ecosystems lies more within the scope of the database, since it can provide descriptive information as to which biological taxa are found where, and under what conditions. An example of the kinds of results which queries of water chemistry and biological data may produce is given in Table 1.

Table 1 summarises the results obtained from a query of three invertebrate families known to be, in order of appearance in the table, very intolerant, fairly intolerant and highly tolerant of extreme water quality conditions, respectively. The ranges of conductivity, pH and sulphate ions at which each family has been recorded were calculated. The upper and lower 2.5% of values were excluded so that possible analytical, taxonomic and/or data capture errors were omitted. There are, however, a number of problems inherent in such a manipulation, most of which are concerned with difficulties with the data themselves. The range of a particular chemical variable associated with a taxon, is only the recorded range at which the particular group of organisms has been found. It is not a measure of actual tolerance ranges, since these organisms may well survive in conditions outside of these ranges, but such zones have either never been sampled, or the animals, while they may never have been exposed to these ranges in natural systems, would nonetheless be quite capable of surviving there. Thus if the recorded ranges are used to gauge tolerance, the values obtained will probably err on the conservative side. Antagonistic or synergistic effects of different chemical variables are not taken into account and these data cannot provide any satisfactory indication of cause and effect in terms of water quality variables and taxon distributions. For example, the cause of a taxon's absence at a site may be due to an event such as an oil spill, which is not recorded in the database but which will, nonetheless, have a profound effect on biotic communities. This problem can, to some extent, be circumvented by including such details in the site descriptions. The onus is then on the user to exercise both caution and discretion in interpreting the results provided by an interrogation of the database. Unfortunately, however, such information is not always available in the literature. At times, for example, critical chemical variables such as heavy metals, which are expensive to analyse, have not been measured.

Temporal changes in water conditions are not taken into account in the recorded tolerance ranges. Samples of both water quality, and biota represent "snapshot" or instantaneous pictures of an ecosystem, and the mere fact that a taxon appears to be present under certain conditions does not mean that it is unaffected in the long term by such conditions. Water conditions at that time may indicate short-term "flushes" of a certain variable; a recent change to which the biota have not yet responded; a past effect from which they have not yet recovered; or a condition under which they really feel no ill effects at all.

Recorded tolerance ranges of different taxa to different variables derived from the database should therefore be used with caution and the problems outlined above should be taken into consideration.

TABLE 1
SUMMARY OF RESULTS OBTAINED FROM QUERIES RUN ON THREE INVERTEBRATE FAMILIES, TO DISCOVER THE RECORDED RANGES OF CONDUCTIVITY, pH AND SULPHATE CONCENTRATION (mg/ℓ). SD = STANDARD DEVIATION, MIN = MINIMUM, MAX = MAXIMUM. EPHEMERELLIDAE ARE INTOLERANT (SASS SCORE = 15), HEPTAGENIIDAE ARE MODERATELY TOLERANT (SASS SCORE = 10) AND CHIRONOMIDAE ARE TOLERANT (SASS SCORE = 2) TO WATER QUALITY IMPAIRMENT.

Chemical variable	Family	Average	SD	Median	Min	Max	Range	n
Conductivity	Ephemerellidae	3.8	2.7	3.1	1.2	16.1	14.9	142
Conductivity	Heptageniidae	14.9	13.2	10.7	1.7	54.1	52.4	247
Conductivity	Chironomidae	42.6	49.7	21.0	2.1	227	224.9	1183
pH	Ephemerellidae	6.18	0.73	6.30	4.4	7.60	3.20	165
pH	Heptageniidae	7.19	0.80	7.30	5.3	8.58	3.28	234
pH	Chironomidae	7.33	0.86	7.48	4.8	8.90	4.10	1000
Sulphate	Ephemerellidae	1.8	2.2	1.1	0.1	17.3	17.2	67
Sulphate	Heptageniidae	12.7	16.1	3.9	0.1	71.8	71.7	181
Sulphate	Chironomidae	55.8	85.6	18.1	0.1	431	430.9	977

Assessing changes in community structure, using historical records

The true strength of the database probably lies in assessing changes in community structure, using historical records, for it provides an excellent record of biological and water chemistry at particular sites, at specific times in the past. In some cases, these records reflect conditions as close to pristine as we are ever likely to be able to record. Pristine or not, they do provide a means of tracking community and water quality changes over time. The Berg River dataset is a good example of this where data from 1951 to 1953 are available for comparison with those of 1978, as well as 1992 and 1993.

Once again, there are some potential pitfalls that ought to be brought to the attention of would-be users. The chief of these is that sampling and analytical methods are not always directly comparable in different studies, particularly those that are separated by long periods of time, during which technical innovations have been made. In addition, as has already been mentioned, the taxonomy of many species is subject to frequent changes.

Verifying and fine-tuning SASS scores

The records of taxon composition at sites of different water quality may prove a useful method of assessing the validity of some of the scores allocated to different taxa used in the SASS scoring system. The data extracted and summarised in Table 1 provide an example of this. The families interrogated represent both high (Ephemerellidae = 15) and low (Chironomidae = 2) scoring groups. The recorded tolerance ranges of such families, as indicated by the database records, provide some means of evaluating the validity of these scores. Families that appear to have very wide tolerance ranges for certain water quality variables should not be allocated high scores. It is also possible that a thorough interrogation of the data may provide clues as to which taxa may be particularly sensitive to certain types of water quality impairment, and thus be potential "indicator" taxa of these conditions. All these uses are, of course, subject to the same limitations as those outlined previously, although the taxonomic constraints are reduced at the family level.

Biotope preferences of specific taxa

It has often been observed that certain taxa are more commonly found in one biotope than another, although this has seldom been shown quantitatively. An analysis of taxa found in different biotopes will give some indication of their biotope preferences. Such information would be of great value, for example when interpreting SASS scores and determining the instream flow requirements of different taxa in relation to biotopes at a site. The inconsistent terminology and methodology with respect to biotope-data reported means that interrogations are most meaningful at upper levels of the hierarchy (i.e. at the levels of stones-in-current and marginal vegetation, for example) and less reliable at lower levels.

Geographical distribution of taxa

The compatibility of Microsoft Access with geographical information systems (GIS) such as PC-ArcView means that maps may be produced from records. The exact utility of this may lie in displaying the taxon distributions and in ascertaining geographical regions where rivers have not been sampled.

Overall utility of the database

This section has dealt at length with problems involved in any utilisation of the database records. These problems have not been emphasised to discourage potential users, but rather that they be made clear from the start, so that methods of circumventing some of them may be found, and where this is not possible, that the strengths and weaknesses of any results may be quite evident. Two other issues should also be stressed: firstly, it would be logistically and financially impossible to obtain a similar set of data today. Secondly, the database includes the only data that reflect historical conditions, which in some instances represent a period when the degree of impairment was less than the present-day conditions.

Conclusion and recommendations

The database, which collates a vast amount of information pertaining to riverine macroinvertebrates and water chemistry, has several useful applications if used with the awareness of the problems outlined in this paper. In establishing this database, one of the problems encountered, that was both difficult to resolve, and unnecessary, was that caused by the lack of consistency in the way in which different authors present their data. Frequently, useful data are lost, merely because they cannot be compared with others. Thus one of the more important recommendations to emerge from this area of work is that future biological and chemical collections should conform to the standard units of measurements laid out in Dallas et al. (1995), in the case of water quality, and that details of proportional abundance, as well as factors such as biotope type, should be considered. In addition, the actual dates on which both biological and chemical data were collected should be available for reference, where they are not actually presented in published reports. The potential exists for this database to form the template for future database development. Other components of aquatic biota such as fish and riparian vegetation could also be incorporated.

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Appendix 1

Study references used in compiling the aquatic macroinvertebrate and chemical database

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