The design and research potential of an artificial stream system for the investigation of macroinvertebrate water quality tolerances

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Abstract

An artificial stream laboratory has been developed at Rhodes University, in collaboration with the Water Research Commission and the Department of Water Affairs and Forestry. It provides a controlled environment, with a defined and replicated range of hydraulic conditions, so that experimental research can be conducted using rheophilous organisms. In the first instance, research will focus on the response of riverine macroinvertebrates to changes in water quality. The system is also ideal for the investigation of hydraulic requirements of riverine taxa. In this paper we describe the role artificial stream research can play in water quality management, briefly review artificial stream designs, and provide design details of the artificial stream system which has been built.

Introduction

Water quality management in South Africa has recently changed from the uniform effluent standard approach, to the receiving water quality objectives (RWQO) approach (Van der Merwe and Grobler, 1990). The implementation of the RWQO approach aims at the maintenance of water quality in a state "fit for use" by any or all of 5 designated water resource users: industry, agriculture, domestic supply, recreation and the environment (Department of Water Affairs and Forestry, 1993). Water is a limited resource which is unevenly geographically distributed, and users compete for water supply. However, the allocation of water to the natural environment, in terms of both quality and quantity, needs to be considered separately from the other users, because the maintenance of river ecosystems and catchments in a state of ecological integrity, where biological processes remain functional, is a prerequisite for meeting most other user requirements. If water quantity and quality are inadequate for the maintenance of ecological function, then many other user requirements cannot be met either. It is therefore imperative that realistic environmental requirements are defined, and management objectives provided.

The Department of Water Affairs and Forestry (DWA & F) has prioritised setting water quality guidelines for all the user sectors. Guidelines for 4 users, but not for the natural environment, have been published (DWA & F, 1993). Setting environmental water quality guidelines that are appropriate to the South African situation has proved to be difficult. Various information sources are available: the historical patterns of chemical concentration can be used; published water quality guidelines set for other countries can be consulted; the natural distribution patterns of freshwater biota can be related to regional patterns of water quality; and ecotoxicological studies can provide experimental results concerning the tolerance limits of specific taxa. These taxa can either be standard laboratory organisms, such as *Daphnia* (Roux et al., 1993), or local South African riverine taxa.

An artificial stream system has been designed and built with the specific aim of providing a controlled flowing water environment, where riverine organisms from local rivers can be subjected experimentally to changes in water quality. In this paper we present:

- a brief review of artificial stream designs;
- a description of the selected design; and
- the operation, and planned experimental use of the system.

Artificial streams - Design alternatives

One of the most obvious features of natural ecosystems is the complexity of interactive effects between abiotic and biotic variables. In an experimental approach, the general aim is to maintain certain variables constant while investigating the effects of others by altering them within controlled limits. Artificial stream research is based on the further premise that the provision of a flowing water environment is fundamental to any experimental research on riverine organisms (Frutiger, 1984).

At the more natural end of artificial stream design spectrum are outdoor systems which allow control of selected variables while leaving others, such as light, daylength and temperature to fluctuate with the natural environment. Such designs offer less experimental control and are favoured by those who believe that "conclusions and generalities from artificial stream systems which incorporate more of the characteristics of natural environments are more directly related to those environments" (Clark et al., 1980). Outdoor systems vary in "naturalness" from channels placed in a stream and naturally colonised (Hildebrand, 1974; Kowanacki et al., 1985; Poff and Ward, 1990); through channels next to a stream with stream water diverted through them (Clark et al., 1980; Bothwell, 1988; Allard and Moreau, 1985; 1987; Eichenbacher et al., 1985 Arthur, 1988); to large recirculating systems (Ladle, 1976, 1977; Reynolds et al., 1990).

Ladle and Frutiger (1991) both regard artificial stream research in large outdoor systems as useful, but caution that it is capital intensive, and requires considerable manpower both for maintenance, and sample and data processing. Other difficulties include

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Received 20 December 1993; accepted in revised form 13 May 1994.

the cost and difficulty of providing replicate systems, and the recognition of considerable between-channel variation. A very large system at the Monticello Ecological Research Station, Minnesota (Arthur, 1988) has provided useful results, but is operated at a scale that is not economically viable in South Africa.

Smaller channels can be housed inside, and offer opportunities for more operational control: "Laboratory streams confer advantages of reduced complexity and increased control, and permit examination of the interaction between physico-chemical variables and biological systems" (Horne and Bennison, 1987a). Laboratory streams generally have channels which range in length from 1 m to 15 m. Channels are usually artificially colonised, water may be recirculated or through flow, and channels may be circular (Higler, 1975; Ciborowski, 1983; Adams et al., 1987; Pontasch and Cairns, 1989) or straight (Whitford et al, 1964; McIntire, 1968; Feldmeth, 1970; Kapoor, 1972; Bott et al., 1977; Clifford et al., 1979; Thirb and Benson-Evans, 1982; Burton et al., 1985; DeNicola et al., 1990).

The large-scale streams we have designed and built are based on a design developed in Australia by Horne and Bennison (1986, 1987a; b). In justifying the development of an Australian artificial stream facility, they noted the limitations of using Northern Hemisphere toxicity data and the paucity of data on responses of local taxa to pollution, and argued that the facility provided an opportunity for collecting data which would be relevant to Australian conditions. These arguments apply equally in South Africa.

Three major criticisms may be levelled at artificial stream research:

- the limited degree to which results are applicable to the natural environment;
- the physical scale of many artificial streams is too small for natural processes to occur; and
- they are usually inadequately replicated, so it becomes impossible to assess within-system variability, and to evaluate between-treatment experimental results in comparison.

The artificial stream laboratory in Grahamstown was designed with these criticisms in mind. We accept that no indoor system can mimic the natural world, but argue that the operational control gained allows valuable opportunities for consideration of both single variables, and complex effluent effects. The system aims to provide a range of hydraulic conditions which can be accurately described, since rheophilous stream organisms have specific hydraulic preferences and requirements (Statzner et al., 1988). The system includes models at 2 scales: large-scale models which aim to adequately model natural physical conditions; and smaller portable models which can be used in the laboratory or in the field.

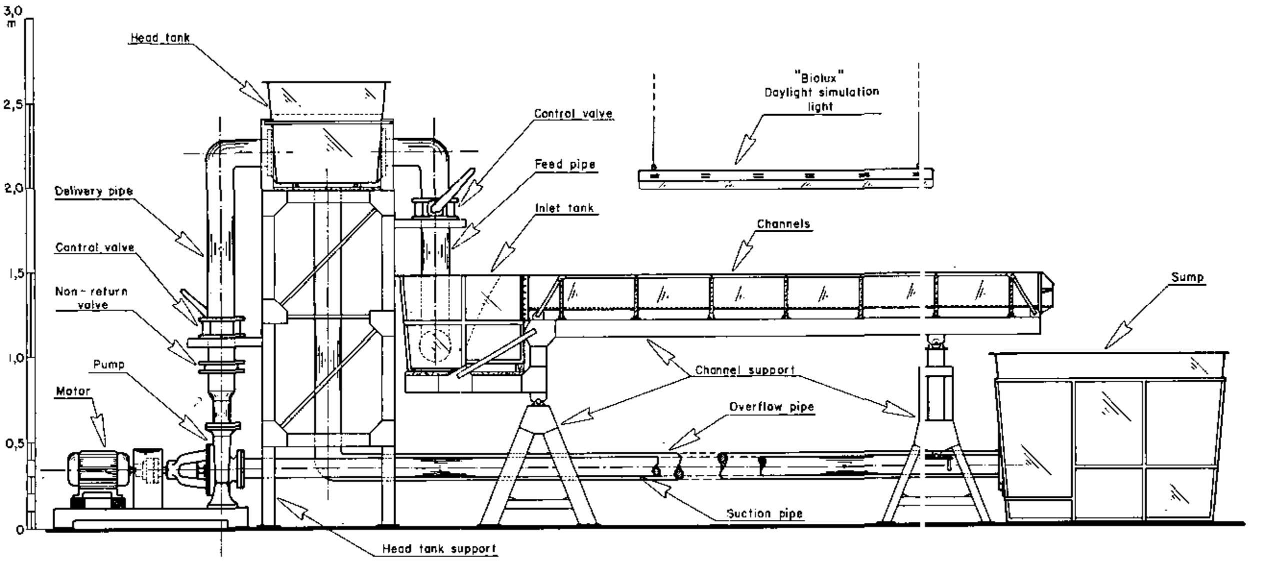

Figure 1

An elevation of one of three 3-channel artificial stream units:

Water is pumped at a constant 20 l/s through a non-return valve (which prevents back-flow through the pump after switch-off or trip) and a control valve, up the delivery pipe into the head tank. Water flows to the perspex channels through a second control valve, via a perforated diffuser pipe in the inlet tank, which contains a shaped tank-to-channel transition to ensure equal delivery to each channel. If the second control valve is set to deliver less than 20 l/s the excess water overtops an internal weir in the head tank, and is returned direct to the sump via the overflow pipe. The suction pipe delivers water from the sump to the pump. The channel gradient can be varied from level to 4% via the adjustable channel support, and a wide range of hydraulic conditions can be achieved by varying discharge and slope.

Design of the large three-channel system

Figure 1 shows the structure and components of a single three-channel unit. Details of the experimental stream units, in the form of detailed drawings, perspective drawings and design sketches are available on request from the 2nd and 3rd authors at the address given.

Design specifications

In the first instance the streams will be used to investigate the tolerances of stream macroinvertebrates to selected water quality variables. However, in order to distinguish organism responses to water quality it is important to define the hydraulic conditions under which they are held, since flowing water fauna are particularly responsive to hydraulic variables (Statzner et al., 1988). Therefore, in addition to water quality control, design criteria required controlled variability over the flow depth and velocity regime in the channels. A variable flow rate to the channels, together with the ability to vary the channel gradient, provides as wide a range as possible of depth and velocity combinations. Water quality control is addressed by the use of materials which will neither affect the quality of the recirculating water, nor be affected by the water.

Three identical three-channel units were built to accommodate a control and 2 experimental units. Each recirculating unit was designed with 3 channels in which the flow regime for any given flow rate was essentially identical.

Design approach

The hydraulic and structural design of each unit proceeded from the specification of the required flow regime in the channels. So as to be able to work with the whole range of rheophilous organisms, flows from low velocities (0.3 m/s) to flows in excess of 1 m/s were required: for example the pest species blackfly *Simulium chutteri* is primarily found in velocities greater than 1 m/s. From this flow rate, appropriate pipe sizes, tank dimensions and the overall dimensions of the unit were progressively calculated.

The selection of an appropriate pumping unit was considerably complicated by the limitations of the power supply to the laboratory site. Although an adequate 380 V 3-phase mains supply was available, Grahamstown's municipal electricity supply is subject to unpredictable outages, which can last for substantial periods. The experimental runs are scheduled to last for a minimum of 96 h, during which pump stoppage due to power failure would have catastrophic effects on the aquatic biota populating the channels, because the channels would drain down very quickly on cessation of flow. It was therefore vital to have an emergency backup power supply available, to come on-line automatically and rapidly in the event of mains supply failure. A backup supply to a maximum of 3 kW was negotiated from a nearby source.

Materials specification

Because of the emphasis in the project on the control of water quality it was decided that all materials directly in contact with water were to be plastic-based: perspex, fibreglass, polyvinylchloride, etc., with documented high levels of chemical resistance. The exceptions were the pump volute casing and impeller, which were nickel-plated cast iron, and bolts on flanged pipework, which were high quality stainless steel. Economy dictated the use of mild steel and timber for the components of the support structures, for which protective coatings were specified.

Channels

Each of the 3 channels followed the basically trapezoidal cross-section of a stream, with a bottom width of 200 mm, depth of 200 mm and a side-wall angle of 70°, giving a top width of a little less than 350 mm. The total width of 3 parallel channels allowing for supporting ribs fixed the overall width of the unit at about 1 200 mm, and therefore influenced the size of tankage. A velocity range of 0.3 m/s to more than 1 m/s was required, together with a depth range of about 30 mm to 60 mm. Initially the use of fibreglass was favoured for the three-channel units, as the material is more robust than perspex, and the unit could have been completely jointless. The cost of this option, however, was prohibitive. In addition, the provision of viewing windows complicated the design. Construction in perspex has the advantage of providing full visibility into all parts of the channels. The channel length is therefore 3 200 mm, to suit the size of standard perspex sheets.

Preliminary analysis of the channel flow regime using the one-dimensional open channel flow package CFP (ECC, 1987) indicated that a maximum flow rate of 20 ℓ/s, with the ability to vary the channel slope between 1% (0.57°) and 3% (1.72°) would achieve this velocity and depth range in a bare channel with no substrate. The hydraulic analysis of the channels is discussed later.

Pipework

The size of pipes was dictated by the necessity of keeping velocities as low as possible, both to reduce internal losses (pipe losses are proportional to the flow velocity squared), and to minimise turbulence on entry into tanks. The hydraulics of the piping system was analysed using the Darcy-Weisbach pipe friction equation (Institution of Water Engineers (IWE), 1969) (with an "f" value for plastic pipes, derived from the Moody Diagram (IWE, 1969), of between 0.016 and 0.017) to calculate pipe friction losses. "Minor" losses in bends, fittings and at pipe entries and exits were calculated using published loss coefficients (IWE, 1969). Pipe runs are short, and minor losses are generally much higher than losses due to pipe friction. Losses through the butterfly and non-return valves were estimated from data provided by the manufacturer/supplier, or from published data for similar valves.

As a result of this analysis a combination of pipes, valves and fittings of nominal internal diameters of 100, 125 and 150 mm was selected, which satisfied the hydraulic requirements of the system, and fitted into the space available in the laboratory. One of the uncertainties in the hydraulic analysis was the exact capabilities of the pump in terms of flow rate and delivery head, but it was recognised that control of the pump delivery could be exercised using the valve on the delivery line, for which purpose the butterfly valve selected is well-suited. The hydraulic analysis also indicated that the control valve on the line from head tank to feed tank would need to be throttled to about half-closed to limit the delivery to 20 ℓ/s, and this proved to be the case. Although these control valves were very expensive they proved to be absolutely indispensable for flow control. The non-return (reflux) valve on the pump delivery line, also an expensive item, was necessary to prevent flow in this line reversing when the pump stops on power failure, which would cause serious damage to the pump when restarted on the backup power supply.

Unplasticised polyvinylchloride (uPVC) pipes are manufactured in South Africa and are relatively inexpensive. The fittings and valves were imported, however, and were very expensive. Costs of pipes, fittings, valves and bolts amounted to about 27% of the total materials costs of each stream unit.

Tankage

All the tanks were cast in fibreglass at DWA & F's Pretoria hydraulics laboratory to specific dimensions dictated by hydraulic and space considerations: it was not possible to make use of proprietary tanks of standard sizes.

Sump

The sump is 1 200 mm square by 1 000 mm deep, with a total capacity of about 1 450 *ℓ*, while the total volume of water in the system was calculated to be a little over 1 700 *ℓ*. Should the pump fail, about 300 *ℓ* is retained in the head and feed tanks, or stored in the low-level pipework, and the capacity of the sump is sufficient for the balance, with a freeboard of about 30 mm.

Analysis, after a method proposed by Kulkarni and Shah (1987), indicated that in normal operation, the water level in the sump was sufficiently high above the pump suction pipe to preclude the formation and ingress to the pump of damaging air-entraining vortices. Under normal operation the water depth in the sump is 700 mm.

A major leak in the system during periods of unsupervised operation could result in the pump running dry, resulting in major damage to the motor. A float switch was installed in each sump, which will trip the pump should the sump water level fall by more than 200 mm.

Head tank

Variation of discharge into the channels is achieved by pumping into a head tank, and thence via a channel feed control valve into the feed tank and channels. A 400 mm high internal sharp-crested weir across the head tank is set so that the maximum flow rate of 20 *ℓ*/s is delivered when the water level stands at the weir crest level. Partial closure of the feed control valve causes the water to overtop the weir, spilling into the reject pipe directly into the sump, with the balance of the flow continuing into the channels. Irrespective of the flow rate into the channels the pump continues to deliver its rated flow against a delivery head which varies by only about 70 mm between zero flow and 20 *ℓ*/s into the channels - essentially a constant delivery head. This flow variation could also be achieved by the use of a variable speed motor, but the additional cost was prohibitive, and had the additional disadvantage of adding considerable complication to an otherwise relatively simple switchgear design.

Feed tank

The purpose of this tank (approximately 1 200 mm x 700 mm x 550 mm deep) is to distribute the flow from the head tank as evenly as possible among the 3 channels. A submerged horizontal diffuser pipe in the tank is perforated with a number of 20 mm dia. holes, which in total have the same area as the incoming pipe cross-section, thereby causing no increase in flow velocity, and arranged in a pattern so that the incoming flow is distributed across the full width of the tank. A shaped transition piece between the tank and the channels ensures that there are no abrupt discontinuities to cause turbulence in the channels. Although difficult both to construct and install, the transitions were observed to perform well.

Pumps

The hydraulic analysis of the pipework, channels and tankage indicated the need for a pump with a rating of 20 *ℓ*/s against a total delivery head of at least 2 m, preferably 2.5 m. This is not a standard head/discharge combination: most proprietary off-the-shelf units capable of pumping 20 *ℓ*/s do so against a delivery head of between 5 and 10 m, and require a motor of 2.2 kW. Delivery through smaller vertical lifts is achieved by destroying delivered head through a throttled delivery valve. This was not an option here, because the available backup power was limited to 3 kW, insufficient to run three 2.2 kW motors (a pump motor is rated for starting, and subsequently draws a little more than half its rated power in normal operation), still less to restart them.

It was necessary to have special units designed, with downrated (reduced speed) motors and oversized impellers, powered by a 1.1 kW motor, and which could therefore run on the available backup power. Nevertheless, to avoid overloading the backup supply, timers were included in the switchgear which, on restart under backup power, will stagger starting of the 3 pumps about 15 s apart.

Pump impeller shafts are fitted with mechanical seals, as standard greased glands can affect water quality. Because the pump is a special, there are no published performance data available. No proving tests were carried out in the manufacturer's works, so that even on delivery the exact duty point (discharge versus head) was known only theoretically. The indications are that the pump delivers its claimed 20 *ℓ*/s against a head in somewhat excess of 2 m: the excess head is destroyed by delivery through a half-closed control valve on the delivery line.

The special pump/motor units were about twice as expensive as a standard higher head unit, and the cost of the pumps and switchgear represented about 30% of the total materials costs of the units.

Structural design

The most important considerations in the design of the support structures were minimisation of deflection under maximum loading conditions, and rigidity.

Channel and feed tank support

Excessive deflection of the steel framework supporting the channels would not only result in variable and unpredictable hydraulic conditions in the channels, but could also overstress the perspex and cause cracking. The maximum deflection of the channel support is limited to 1 mm by the use of a primary frame out of 100 x 50 x 2 mm rectangular mild steel tubing, ledged with 50 x 50 x 2 mm square tubing. The feed tank support, in the larger sized tubing, is cantilevered from the channel support frame. In terms of strength this approach results in considerable overdesign: the maximum tensile stress in the main members was calculated to be only 12% of the permissible stress. Rigidity is provided by the use of substantial steel plate gussets at all joints.

Trestles

The rear (fixed) trestle, which carries about 75% of the total load of the channel/feed tank system, is considerably sturdier than the front (adjustable) trestle. Both are bolted to the laboratory floor. Two lifting mechanisms comprising 24 mm dia. square threaded rods in the front trestle facilitate adjustment of the channel gradient. The joint between the rear trestle and the channel support is essentially a hinge, whilst rollers at the head of the front trestle accommodate longitudinal movement of the channel support during gradient adjustment.

Head tank support

In addition to a working load, in excess of 300 kg, of the head tank and associated pipework and valves, this 2.4 m high structure was designed to carry the full weight of at least one person engaged in operational and maintenance activities. Its main members are 100 x 100 x 2 mm square tubing. It is firmly bolted to the laboratory floor.

Shortcomings in the design

In general the 3 large recirculating units perform as expected, and provide a flowing water environment in the channels with a considerable range of depth and velocity combinations. It is clear, however, after some months of operation, that some aspects of the design could be improved.

Tankage

Pipe joints

Jointing of pipes into tanks was effected by bolting through the tank walls using PVC stub flanges/backing rings and rubber gaskets. This gave rise to some difficulties in sealing the considerable number of possible leakage paths - extensive use was made of silicon sealant, which probably has a useful life of about 3 years. A better solution would have been to have the tanks fabricated in welded polypropylene sheet, into which flanged stub pipes can be welded. This option was investigated at design stage, but the cost proved to be beyond the project resources.

Channel feed tank

The transition unit at the head of the channels was designed to facilitate a smooth transition from the feed tank into the 3 channels, avoiding abrupt cross-sectional changes and associated turbulence in the channel flow regime. Hydraulically it performs well, but with hindsight it was over-sized, extending too far down into the tank, and difficulty was experienced in sealing the unit into the tank.

Joints

Joint between channel feed tank and channels

The requirement for a degree of modularity in the stream unit precluded glueing of this joint, and the joint was sealed using quite large quantities of silicon sealant. The relatively brief life of this material indicates the need for regular maintenance on this important joint. The use of fibreglass was considered for the channels at design stage, which would have made a bolted/gasketed joint possible here, but the cost was prohibitive.

In general too much reliance was placed on the use of silicon sealant.

Channels

Initially fibreglass was the preferred material for the channel units, because the material is tougher than perspex, and the unit could have been completely jointless. Apart from cost considerations, the provision of viewing ports in the channels complicated the design. Hot moulding the perspex to form jointless channels was also considered, but required an oven larger than any available.

Overflow from head tank to sump

Water overtopping the head tank weir falls directly into the overflow pipe, entraining air which is carried into the sump, causing some turbulence and splashing. A perspex splash cover at the sump addresses the symptoms, but some form of baffle in the head tank could solve the problem at source.

Steelwork

All steelwork was etch-primed and painted with corrosion resistant paint, which according to the manufacturer's instructions did not need further coating. However, after only a few month's operation the steelwork shows some surface rusting, and will require attention. Application of a gloss finish would have been more effective - possibly a chlorinated rubber coating.

Small-scale model or raceway design

Small-scale models were constructed on a raceway design (Ciborowski, 1983). Each raceway is constructed from 5 mm perspex, set into and glued to a perspex base which is reinforced by a 25 mm marine-ply wood base (Fig. 2). The channel width is 125 mm, and the working length 470 mm. Water is recirculated by a paddle wheel driven by a Bosch CHP 12v (9 390 292 085) windscreen-wiper motor screwed to the wood base in the centre of the raceway well. The motor was selected so it would run in the field using a DC energy source, such as a car battery, and can also be powered by the mains supply in the laboratory via a transformer/rectifier. The 2 motor speed settings provide the opportunity for 2 different speed settings for the paddle: at the higher motor speed, 60 r/min, the 330 mm dia. paddle has a peripheral speed of 1 m/s, while the lower speed of 45 r/min produces a paddle peripheral speed of 0.75 m/s. In the first model we used a variable resistor to alter speed, but at low speeds the motor overheated. The motors operate reliably for periods of several weeks at either of the 2 given settings.

The most serious problem with the raceways has been leaking. Despite reinforcement of the channel sides with perspex buttresses, transporting or moving the raceways stresses the joints sufficiently to cause leakages. To date this has not been solved, and it means there is time wasted in maintenance.

Laboratory layout and experimental design

Three 3-channel units are accommodated lengthwise in the artificial stream laboratory, and 3 raceways are associated with each unit. This allows each experiment to run at 2 scales. Single variables can be selected and maintained at different experimental levels in each unit. Portable raceways can subsequently be taken into the field, and the experiment repeated under river-side conditions using river water and freshly collected animals. In this way the small-scale raceways are used for "field verification" of the large-scale channel systems, with laboratory raceways providing a comparison of scale effects.

The laboratory systems require a ready supply of experimental animals and additional raceways are kept in the laboratory for rearing experiments.

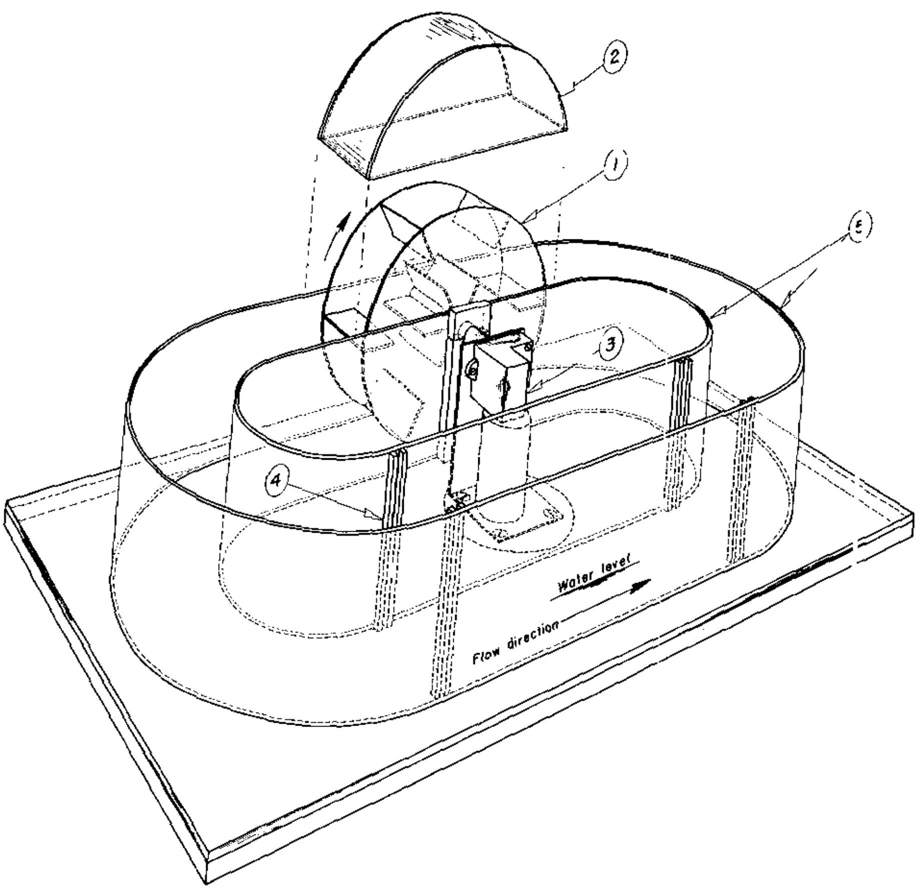

Figure 2
Diagram of a perspex, portable raceway which is used both as a small-scale model in the artificial stream laboratory, and in the field

In addition to the hydraulic control offered within each unit, other factors such as temperature, daylength and light can also be controlled in the laboratory. Light is provided by OSRAM "biolux" tubes which provide a full spectrum of wavelengths, similar to sunlight. Intensity is controlled by suspending the lights on chains, so their height above the channels can be adjusted. Lights are on a daylength adjustable timer. Air temperature control is provided by two Sanyo SA246SE (24 000 btu) air conditioners which allow control within 1°C, between 21 and 24°C. Water circulated through the channels can be heated to 26°C, as the pumps heat the water, and cooled to 14°C by epoxy coated copper cooling coils in the sump through which the coolant R22 is circulated by a compressor. For any experimental period at a particular temperature setting, water temperature is maintained within a 2°C range.

In experiments where water quality variables are altered, the starting water quality must be specified. There is a range of alternatives. The laboratory is supplied with municipal tap water, there is a *10 000 ℓ* rain-water tank outside, and local river water could be brought in by water tanker.

Discussion

Artificial stream research provides the opportunity of controlling variables, both physical and chemical, in a way that is impossible under field conditions. This means that the role of individual variables, and combinations of variables can be investigated. However, artificial stream research has limitations. The natural environment, with all its inherent variability is exchanged for operational control, which calls into question the applicability of results in the field. However, there are questions of pressing concern which are intractable to field research. These include questions about the tolerances of indigenous riverine fauna to changing water quality conditions.

Bioassessment and field distribution studies can provide correlative data concerning the environmental abiotic ranges within which natural populations survive. Such studies cannot, however, distinguish the effect of individual water quality variables; and other factors (such as biotic interactions) may restrict the distribution of a species to conditions well within its tolerance range. The absence of a species cannot necessarily be related to deteriorating water quality. Field distribution studies therefore cannot provide information on the tolerance limits of species to single water quality variables, or to complex effluents. This is the role of ecotoxicology (Metcalfe-Smith, 1991).

There are several toxicity testing options, including: the choice between the use of standard laboratory organisms or local riverine organisms; the choice between standing- or flowing-water test systems; in flowing systems the choice between through-flow and recirculating systems; the choice between lethal and sublethal tests (e.g. behaviour, growth, or reproduction); and in lethal tests the choice between acute (up to 96 h), sub-acute (4 to 7 d) or chronic (longer than 7 d) testing. In lethal testing the LC50, or lethal concentration at which 50% of the population dies, is the standard measure of response.

In South Africa, toxicity testing already has a role in water quality management: when DWA&F receives requests to grant a permit for effluent disposal, the toxicity of the effluent to biotic components is tested using standard laboratory organisms, and a battery of acute and chronic tests. This could be extended in that toxicological objectives could be included in permit requirements. Compliance with such effluent standards would be monitored routinely by the polluter, using toxicity tests. This would usually involve the use of standard laboratory organisms.

The artificial stream laboratory provides flowing water recirculating systems in which indigenous riverine organisms can be subjected to lethal or sub-lethal tests. There are 3 main applications):

- If routine bioassessment indicates a water quality problem by the decline or disappearance of specific taxa, taxonomic composition can be correlated with a range of variables, using multivariate statistics, to indicate the possible causative factor/s. The responses of taxa which were in the stream can be tested at a range of concentrations to establish LC50, and NOEL (no observed effects level) values, which could be used to provide the polluter with a range of limits for effluent concentrations.
- Environmental water quality guidelines can be refined at any chosen scale from river reach, to river, to ecoregion, using organisms typical of the chosen system. Specific ecosystems, and variables of concern can be selected, and a data base developed with information which links the indirect methods of setting guidelines to specific riverine conditions at a spatial scale selected by water quality managers.
- The toxicity of whole effluents can be tested in the field using river water and organisms from the proposed receiving water.

In conclusion, we suggest that the artificial stream laboratory provides the facilities to form a valuable part of a suite of available toxicity testing options, which in turn are part of the wider arena of water quality management. In addition to water quality research, the systems are ideal for investigating the precise hydraulic preferences of stream organisms. This has applications in providing water quantity guidelines. At changing discharges the proportional availability of various hydraulic conditions changes, with information on hydraulic habitat preferences predictions could be made concerning the biological consequences of altered flow regimen. And in addition to freshwater research, the systems can be filled with water of any of a range of salinities, and with suitable modifications to reduce flow velocities, be used to simulate estuarine conditions.

Acknowledgements

The project is funded by the Water Research Commission, and the Department of Water Affairs and Forestry provided expert assistance in the design and construction, and also in the planning of future research directions. Others who have made significant contributions to the project are Jay O'Keeffe, Qurban Rouhani, Brenton Maart, Gaye Youthed, Kekere Soxujwa and Patsy Goetsche, all of the Institute for Water Research, Rhodes University.

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Appendix 1

Large multi-channel systems: Details of equipment and materials

Pumps, motors and switchgear

Pump/motor units: AZG 100-200/180 CI/CI/MS all-iron pumps, to deliver 20 ℓ/s against ±2.5 m head, each mounted on a common mild steel baseplate and direct- coupled to a 1.1 kW 6-pole 380 V 3-phase motor. The pump has a 180 mm dia. impeller, 125 mm dia. suction flange, 100 mm dia. delivery flange, and is fitted with mechanical seals.

Starter/control panel: Switchgear is contained in a mild steel cabinet fitted with door-interlocked circuit breaker and a voltmeter with a 3-position selector switch, and comprises for each of 3 pumps a starting contactor, overload relay, run ammeter, stop/run selector, power-on/run/trip indicators and a 3-pole circuit breaker. A mercury float switch in each sump trips the pump should the water level in the sump drop to unacceptably low levels. An adjustable timer is fitted to each starter to facilitate staggered restart after mains power failure, to avoid overloading the back-up power supply.

Pipework, fittings and valves

- All pipework is Class 4 (±4 bar pressure rating) uPVC Type 1 of 110, 125 and 160 mm outside dia.
- Fittings (bends and tees) are PVC with solvent welded joints to pipes.
- Joints to tanks and valves are by means of glued PVC stub flanges with bolted PVC backing rings and EPM (ethylene-propylene copolymer) gaskets. Bolts at tank joints are stainless steel; all other bolts are mild steel.
- Control/isolating valves are fitted on the delivery lines between the pumps and head tanks, and between the head tanks and channels: these are 150 mm dia. rapid action butterfly valves of all-plastic and stainless steel construction.
- Non-return (reflux) valves are fitted on the delivery lines immediately above the pumps: these are 150 mm dia. wafer-type valves with polypropylene bodies and discs, without spring disc reset.

Channels

Channels and head tank weirs are in 6 and 8 mm thick polymethylacrylic (acrylic sheeting or perspex) sheet, with solvent-glued joints.

Tankage

All tanks are cast in fibreglass, using Crystic 406PA low exotherm general purpose polyester resin with chopped strand glass mat: a minimum wall thickness of 6 mm was achieved, and the sumps were reinforced with cast-in 19 mm square steel tubing.

Support structure

The steel support structures are in welded mild steel square and rectangular tube and flat bar, etch-primed and painted with corrosion-resistant paint. Platforms for head and feed tanks, and channel support ribs are in heavily varnished marine ply 20 mm thick.

Appendix 2

Hydraulic analysis of large system channels

Flow in the 3 channels was analysed using the one-dimensional open channel flow software CFP (channel flow profiles) (ECC, 1987), for a range of flows up to 25 ℓ/s, and for a range of channel gradients from 0% to 3%.

For a bare channel with no substrate a value of 0.009 was used for the Manning's "n" roughness coefficient (Chow, 1959). Tables 1a to 5a give calculated average velocities and depths of flow on the channel centre lines for flows of 10, 15, 20 and 25 ℓ/s and channel gradients of 0, 0.5, 1, 2 and 3%. Results are given at 400 mm intervals, from a point 400 mm from the upstream end of the channel to a point 400 mm from the downstream end, ignoring the transitional lengths from the feed tank and into the free overfall into the sump. Figure 3 is a generalised plot of the depth and velocity results for the bare channel case which indicates the range of depths and velocities to be expected for the middle 1 600 mm section of the channel, the probable test section, for each flow rate and channel slope. The flow rate lines are envelopes of the individual plots of depth against velocity at each calculation point along the channel.

Analyses were also carried out for 2 possible substrate cases: two 50 mm size stones at 100 mm intervals along the channel and; two 40 mm size stones at 100 mm intervals along the channel, in a general pebble matrix 25 mm thick. The results are presented in summary as a comparison with the bare channel results (Table 6a).

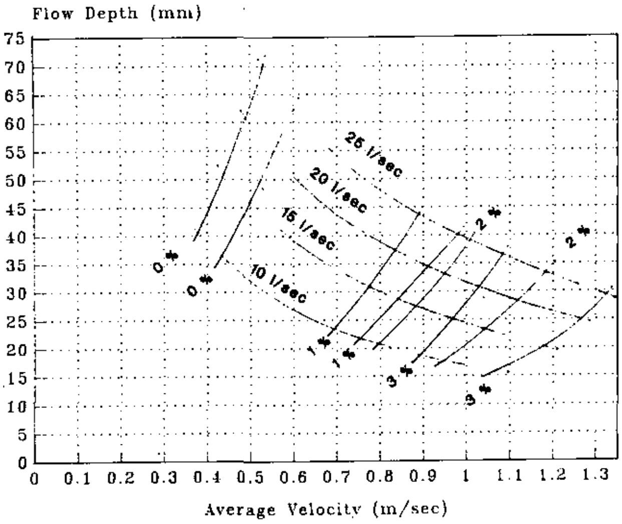

Figure 3
A generalised plot of calculated average velocities and centre-line depths in the middle 1 600 mm of a channel with no substrate, showing the expected range of depth and velocity combinations at flow rates of 10, 15, 20 and 25 l/s, and at channel gradients of 0, 1, 2 and 3%

TABLE 1a
DEPTH-VELOCITY CALCULATIONS, AT 400 mm INTERVALS DOWN THE LENGTH OF THE CHANNEL, FOR FLOW RATES OF 10, 15, 20 AND 25 l/s. SLOPE SETTING - 0%. FLOW IS SUB-CRITICAL AT ALL FLOW RATES.

Distance along channel (mm)	**10 l/s**		**15 l/s**		**20 l/s**		**25 l/s**	
	Depth (mm)	**Vel. (m/s)**	**Depth (mm)**	**Vel. (m/s)**	**Depth (mm)**	**Vel. (m/s)**	**Depth (mm)**	**Vel. (m/s)**
400	41	0.37	52	0.44	62	0.49	71	0.53
800	41	0.38	51	0.44	60	0.49	70	0.54
1 200	40	0.39	50	0.45	59	0.50	68	0.55
1 600	39	0.40	49	0.46	58	0.52	67	0.56
2 000	38	0.41	48	0.48	57	0.53	66	0.57
2 400	37	0.43	47	0.49	55	0.55	63	0.59
2 800	35	0.45	45	0.52	53	0.57	61	0.61

TABLE 2a
DEPTH-VELOCITY CALCULATIONS, AT 400 mm INTERVALS DOWN THE LENGTH OF THE CHANNEL, FOR FLOW RATES OF 10, 15, 20 AND 25 l/s. SLOPE SETTING - 0.5% AT THE MIXED FLOW REGIME FOR 10 l/s, * INDICATES SUBCRITICAL FLOW. FLOW FOR HIGHER DISCHARGES IS SUPERCRITICAL, BUT WITH A FROUDE NUMBER CLOSE TO UNITY. WATER SURFACE IS LIKELY TO BE WAVY, AND GRADIENT IS NOT LIKELY TO PRODUCE STABLE FLOW CONDITIONS.

Distance along channel (mm)	**10 l/s**		**15 l/s**		**20 l/s**		**25 l/s**	
	Depth (mm)	**Vel. (m/s)**	**Depth (mm)**	**Vel. (m/s)**	**Depth (mm)**	**Vel. (m/s)**	**Depth (mm)**	**Vel. (m/s)**
400	29	0.59	36	0.66	43	0.72	50	0.77
800	27	0.59	35	0.68	41	0.73	49	0.78
1 200	27	0.60	35	0.68	41	0.74	49	0.79
1 600	36	0.45*	35	0.68	40	0.75	46	0.80
2 000	38	0.41*	35	0.69	40	0.76	46	0.81
2 400	41	0.39*	35	0.70	40	0.77	47	0.81
2 800	31	0.52*	34	0.70	40	0.77	47	0.81

TABLE 3a
DEPTH-VELOCITY CALCULATIONS, AT 400 mm INTERVALS DOWN THE LENGTH OF THE CHANNEL, FOR FLOW RATES OF 10, 15, 20 AND 25 ℓ/s. SLOPE SETTING - 1%. FLOW IS SUPERCRITICAL AT ALL FLOW RATES.

Distance along channel (mm)	10 ℓ/s		15 ℓ/s		20 ℓ/s		25 ℓ/s	
	Depth (mm)	Vel. (m/s)	Depth (mm)	Vel. (m/s)	Depth (mm)	Vel. (m/s)	Depth (mm)	Vel. (m/s)
400	24	0.65	33	0.73	39	0.79	46	0.83
800	23	0.70	30	0.78	37	0.83	44	0.88
1 200	23	0.71	30	0.80	37	0.86	43	0.91
1 600	23	0.73	30	0.82	36	0.88	42	0.93
2 000	22	0.74	29	0.83	35	0.90	41	0.95
2 400	21	0.74	29	0.84	34	0.91	40	0.97
2 800	21	0.75	28	0.85	34	0.92	39	0.98

TABLE 4a
DEPTH-VELOCITY CALCULATIONS, AT 400 mm INTERVALS DOWN THE LENGTH OF THE CHANNEL, FOR FLOW RATES OF 10, 15, 20 AND 25 ℓ/s. SLOPE SETTING - 2%. FLOW IS SUPERCRITICAL AT ALL FLOW RATES.

Distance along channel (mm)	10 ℓ/s		15 ℓ/s		20 ℓ/s		25 ℓ/s	
	Depth (mm)	Vel. (m/s)	Depth (mm)	Vel. (m/s)	Depth (mm)	Vel. (m/s)	Depth (mm)	Vel. (m/s)
400	22	0.74	30	0.81	36	0.87	42	0.92
800	20	0.81	26	0.89	32	0.95	40	1.00
1 200	18	0.85	25	0.94	31	1.01	37	1.06
1 600	18	0.88	24	0.98	30	1.05	36	1.10
2 000	18	0.91	24	1.01	29	1.08	34	1.14
2 400	17	0.92	23	1.03	28	1.11	34	1.17
2 800	17	0.93	23	1.05	28	1.13	32	1.19

TABLE 5a

DEPTH-VELOCITY CALCULATIONS, AT 400 mm INTERVALS DOWN THE LENGTH OF THE CHANNEL, FOR FLOW RATES OF 10, 15, 20 AND 25 ℓ/s. SLOPE SETTING - 3%. FLOW IS SUPERCRITICAL AT ALL FLOW RATES.

Distance along channel (mm)	10 ℓ/s		15 ℓ/s		20 ℓ/s		25 ℓ/s	
	Depth (mm)	Vel. (m/s)	Depth (mm)	Vel. (m/s)	Depth (mm)	Vel. (m/s)	Depth (mm)	Vel. (m/s)
400	20	0.80	27	0.88	34	0.94	40	0.98
800	18	0.90	24	0.98	31	1.05	36	1.09
1 200	17	0.96	23	1.06	29	1.12	35	1.17
1 600	17	1.01	22	1.11	27	1.18	34	1.23
2 000	16	1.04	21	1.14	26	1.22	32	1.28
2 400	16	1.06	20	1.17	25	1.26	30	1.32
2 800	15	1.07	20	1.19	24	1.28	29	1.35

TABLE 6a

DEPTH-VELOCITY CALCULATIONS, AND FLOW REGIME AT 4 SLOPES, AND 4 FLOW RATES, WITH 2 SUBSTRATE TYPES:

1. TWO 50 mm STONES, EVERY 100 mm DOWN THE LENGTH OF THE CHANNEL
2. A PAVEMENT OF 25 mm PEBBLES, WITH TWO 40 mm STONES EVERY 100 mm DOWN THE LENGTH OF THE CHANNEL.

THIS IS A SUMMARY OF RESULTS FOR THE MIDDLE 1 600 mm OF THE CHANNEL.

Substrate condition		50 mm stones (n = 0.03)			40 mm stones in 25 mm thick matrix (n = 0.022)		
Slope %	Flow (ℓ/s)	Velocity range	Depth range	Flow regime	Velocity range	Depth range	Flow regime
0	10	0.28-0.33	55-46	Sub	0.30-0.36	50-45	Sub
	15	0.33-0.40	68-57	Sub	0.36-0.43	63-53	Sub
	20	0.38-0.45	78-66	Sub	0.41-0.48	70-62	Sub
	25	0.42-0.49	87-75	Sub	0.45-0.52	80-70	Sub
1	10	0.39-0.40	40-39	Sub	0.47	33	Sub
	15	0.46-0.47	50-49	Sub	0.54	43	Sub
	20	0.51-0.53	59-57	Sub	0.60	50	Sub
	25	0.55-0.57	67-66	Sub	0.66	57	Sub
2	10	0.50	34	Sub	0.58	27	Super
	15	0.56	41	Sub	0.67	35	Super
	20	0.63	48	Sub	0.75	41	Super
	25	0.70	53	Crit	0.81-0.82	47-46	Super
3	10	0.55	30	Super	0.66	24	Super
	15	0.64	38	Super	0.76-0.77	31-30	Super
	20	0.71	44	Super	0.84-0.85	37-36	Super
	25	0.77	50	Super	0.90-0.93	43-41	Super

Appendix 3

Hydraulic analysis of large system pipework

Pipe friction losses calculated using the Darcy-Weisbach equation (IWE, 1969):

$$h_p = f.l.v^2 / 2.g.d$$

where:

h_p = friction headloss in pipe (m)
f = friction factor (0.016 to 0.017 for uPVC pipes of dia. 100 to 160 mm, assuming an absolute roughness of 0.01 mm)
l = length of pipe (m)
v = average velocity in pipe (m/s)
g = acceleration due to gravity (9.81 m^2/s)
d = pipe internal diameter (m)

Minor pipeline losses (bends, fittings, entry and exit losses) calculated using the expression

$$h_m = k.v^2 / 2.g$$

where:

h_m = headloss (m)
k = loss coefficient from IWE (1969)