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Environmental requirements and tolerances of Rainbow trout (*Oncorhynchus mykiss*) and Brown trout (*Salmo trutta*) with special reference to Western Australia: A review

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Fish for the future

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Abstract

Both Oncorhynchus mykiss *(rainbow trout) and* Salmo trutta *(brown trout) have a long history of translocation and culture and a wide knowledge base exists.* O.mykiss *is being considered as a candidate for inland aquaculture in the salinity affected areas of southern Western Australia and this review aims, in part, at providing relevant information to those considering a trout-framing venture in Western Australia. Both species of trout can survive a wide range of environmental conditions, including temperature, salinity, pH, dissolved oxygen and ammonia, with* O.mykiss *having a higher temperature tolerance than* S.trutta. *However, within the ranges of environmental conditions, each species has a preferred range within which survival and growth are optimal. Furthermore, survival within these ranges will be affected by synergistic interactions among variables (for example temperature and dissolved oxygen) and the presence of certain features within a habitat (for example cover and refugia). Although not conclusive, many studies suggest that selective breeding programs may be able to produce fish with increased tolerances and better survival under more extreme conditions. In the south-west of Western Australia, a selective breeding program may produce more heat-tolerant fish, presenting opportunities for trout production under a wide range of temperature conditions. Rainbow and brown trout also form the basis of a significant recreational fishery in southern, inland Western Australia and additional environmental influences on stocks within this fishery are also considered.*

1.0 Introduction

Salmonids are one of the most widely studied group of fishes world-wide due to their high value, growth rate, biologically interesting life-cycle and history of translocation across many continents. As a result, a large volume of literature is available on biology and ecology of this group of fishes. Many of these studies are useful for preliminary investigations of the potential for translocating specific strains of trout to new locations which may be at the extremes of trout tolerance, for example, high temperatures experienced during summer in Western Australia. Further, there may be an opportunity to develop or improve strains more tolerant to local environmental conditions, including high temperatures.

Trout were translocated into Western Australia in the late 19th Century, up until the 1980's, to supply a sport-fish species for recreational anglers (Molony et al. 1999; Molony and Morrissy 2000; Chappell in press). Currently, both rainbow and brown trout are stocked into south-west freshwaters (rivers, impoundments and irrigation dams) by the Department of Fisheries to support a freshwater angling fishery in the south-west (Figure 1) with approximately 12 000 licence holders who catch approximately 8 tonnes of trout per annum (Molony 2000). Western Australia has a small trout aquaculture industry, that produces trout for private fish-out and human consumption, which produced approximately 20 tonnes of rainbow trout in the 1997/98 financial year. However, Western Australia currently imports far more trout per annum than are produced within the State and thus there is the potential for an expansion of the local trout industry to meet local demand. Describing and quantifying the tolerances and requirements of trout will be an important step in developing a larger and more productive trout industry in Western Australia.

A first step in expanding and enhancing the local trout industry in WA is to examine the tolerances and environmental needs of trout to provide information for the selection of appropriate sites for trout culture. As a result, an extensive review of the literature of brown (*Salmo trutta*) and rainbow (*Oncorhynchus mykiss*) trout in relation to tolerances to environmental variables and habitat requirements was undertaken. The aim was to summarise the available data to detail the ranges of individual environmental variables under which trout culture is possible and/or optimal. Further, the habitat requirements of trout were also collated to provide information on habitat requirements and possible enhancement of the trout-carrying capacity of streams and impoundments in the south-west of WA. The information summarised in this review may allow a starting-point to estimate the feasibility and sustainability of trout in put-and-take recreational fisheries and culture in a wide variety of water bodies in Western Australia. These waters not only include the cool, freshwaters of the south-west, but also include inland saline water bodies arising in part from rising saline water tables in areas where natural forest has been cleared (e.g. parts of the Wheatbelt, See Anonymous 1999).

2.0 Tolerances of trout to environmental variables

Historically, the tolerances of fish, including trout, to a single environmental variable have been tested to determine the range of a variable under which a species of fish could survive. Physical variables were most often tested due to the understanding that ectothermic animals, and animals in general, can survive within a range of a single variable before regulatory mechanisms cease to cope and the animal either;

1. moves to an area where the variable is at a level favourable to the animal;
2. expends more energy on regulatory mechanisms at the expense of growth or reproduction; or
3. perishes.

Most animals, including fishes, possess a quite a wide tolerance to a single variable. For example, *O.mykiss* can survive in waters between approximately 0.0 °C and 29.8 °C , depending on the temperature history and strain of the fish being tested (Rodgers and Griffiths 1983; Currie et al. 1998) and the rate of temperature change (Elliott and Elliott 1995). However, within this temperature range for survival, or for any other variable, *O.mykiss* have a preferred range in which growth, reproduction and/or other physiological characteristics are optimised (Peterson and Meador 1994). In the literature reviewed, many of the references were based on relatively short-term experiments (96-168 h, see Currie et al. 1998) and therefore long-term effects, such as reduced growth rate or reproductive success, have not been adequately assessed or quantified. An exception is the study by Pankhurst et al. (1996) who demonstrated severe disruption to gonad development in *O.mykiss* exposed to constant high water temperatures (>15 °C) in experimental systems in Tasmania. It should also be noted that within Western Australia, apart from hatchery operations, the most significant utilisation of trout is based on put-and-take recreational fisheries or grow-out farming operations and hence impacts on reproduction are only commercially significant to hatchery operations, of which there are only a few currently within WA.

2.1 Temperature

Temperature is the most often tested variable in many fish studies, including studies involving trout. Temperature is also critical in Australian studies as many species of trout survive and grow best in cool water (5 °C to less than 20 °C , see figure 2 for growth response data) and water temperatures of shallow rivers and dams commonly exceed 25 °C in WA during summer (T.Church, pers. comm.), approaching a potentially critical temperature for trout survival (Currie et al. 1998).

From many studies, the critical thermal maxima (CTM) for *O.mykiss* is approximately 24 - 26 °C (Bidgood 1980). [CTM's are calculated by steadily increasing the temperature of a water body until fish movements become disorganised and/or its sense of balance is upset and normal activity is no longer possible (Currie et al. 1998)]. However, some studies have found lower and higher CTMs depending on thermal history of the fish and life stage. For example, Rodgers and Griffiths (1983) found that *O.mykiss* could survive higher temperatures (to 29 °C) if food was available to excess. Ojolick et al. (1995) and Benfey (1996) recorded that the CTM for brook trout (*Salvelinus fontainalis*, a closely related salmonid) was up to 29.8 °C depending on the age and sex of the fish. Further, Benfey (1996) concluded that females had a higher CTMs than males, and that younger fish were better able to survive higher temperatures than older fish. Thus, it seems that young fish (e.g.

yearlings) may be the best able to tolerate extremes of temperature and should be stocked in preference to older fish and fry. However, in Western Australia, there is a long history of releasing trout as fertilised ova or fry, with fewer fish stocked as yearlings, 1+ or older hatchery ex-broodstock.

S.trutta are reported as having slightly lower maximum CTMs when compared to *O.mykiss*. For example, many authors report CTMs for *S.trutta* up to 23.5 - 26.7 °C, with an optimal range of 8 - 17 °C (Barton 1996) and better sperm viability has been observed in *S.trutta* held in Western Australian waters that do not exceed 18 °C (Molony, pers. obs.). Thus, although both species of trout can tolerate a range of high temperatures, *O.mykiss* can tolerate slightly higher temperature than *S.trutta*, especially when reproductive success is examined (see Section 2.).

A large number of studies have also examined the effect of low temperatures on survival. The overall conclusion is that the critical thermal minima of *O.mykiss* is approximately 1 °C (Finstad et al. 1988) to 2 °C (Belkovskiy et al. 1991). However, at low temperatures feeding and digestion may be halted (Belkovskiy et al. 1991) or development slowed (Hubert and Chamberlain 1995). Although *O.mykiss* have a lower critical temperature for survival, in the south-west of Western Australia the minimum water temperatures do not regularly approach these extremes. Therefore, the lower temperature limit for trout is less critical for this review.

Finally, the CTM for trout can be modified by altering the acclimation temperature of fish and the rate of change. In many cases, increasing the acclimation temperature by 5 °C increases the CTM by 1 °C, between acclimation temperatures of 10-20 °C (Currie et al. 1998), although studies involving higher acclimation temperatures are rare (see Kaya 1978). The rate of temperature change is also critical. Broadly, there are two categories of changes; a static technique, where fish are plunged directly into water of a different temperature; and a dynamic system, where water temperature is changed at a pre-set rate (Currie et al. 1998). Although both techniques are common, Elliott and Elliott (1995) suggested that CTM decreases with increased rate of temperature change, and recommend changes of water temperature between 1 - 2 $°C.h^{-1}$ to provide the highest precision of CTM. Consideration of the rate of change in dynamic tests should also be applied to the tolerance testing of other variables, for example, salinity and dissolved oxygen. As a general rule, Boyd and Tucker (1998) recommend a maximum rate of temperature change of 0.5 $°C.min^{-1}$ for changes of more than 5 °C or thermal shock and death may occur.

As both species of trout have been cultured in Western Australia for several decades, it may be possible that selection for local conditions (high temperatures) may have occurred. For example, a recent trial at the South West Freshwater Research and Aquaculture Centre (SWFRAC), Pemberton (Figure 1), demonstrated that the hatchery strain of *O.mykiss* (65-321.6 g) survived approximately twice as long as a "wild" line (28.4 – 391.2 g) at extreme temperatures (27.5 °C) (Molony, unpublished data). The hatchery strain of *O.*mykiss had been maintained for at least 39 years without the addition of new genetic material at the SWFRAC, in shallow (0.7 m) ponds with little thermal buffering capacity. In contrast, the "wild" line was collected from a self-sustaining population within Serpentine Dam where, due to the depth of the dam, cool water refuges were present even during the height of summer. Although selection for extreme temperatures seems to have occurred passively in the SWFRAC population (i.e. extreme summer temperatures have resulted in mortalities of some brood fish while other brood fish survived), a genetic selection program may result in the development of an even more temperature tolerant strain of rainbow trout. Further, the production of “hybrid” lines of *O.mykiss* (hatchery line x wild line) may increase the tolerance to environmental variables, including temperature, due to “hybrid fitness”. However, studies at the SWFRAC did not find evidence of hybrid vigour or any effect of size in *O.mykiss* in relation to survival at high temperature (27.5 ºC) (Molony, unpublished data).

2.2 Salinity

Salinity has also been extensively studied due to the anadromous life-cycle of many species of trout. In Western Australia, salinity may be important not only for trout survival, but also due to the encroachment of saline waters in the upper reaches of some river systems and the effects on trout, both direct effects on ionic balance (e.g. changes in growth rate and/or survival), and indirect effects (e.g. changes in prey type and availability or water clarity). Tolerance to salinity is also another important consideration for any inland saline culture of trout. However, it should be noted that the salt composition of inland saline waters varies from seawater and is likely to vary among locations.

O.mykiss appear to be well adapted to rapid changes in salinity and are often directly transferred from fresh to oceanic waters in aquaculture grow-out situations. Finstad et al. (1988) reported that *O.mykiss* (40 - 120 g) tolerated direct transfer from freshwater to 26 ‰ without “any visible signs of stress”. However, mortalities were recorded at low temperatures (1 ºC) and it appears that the interaction of temperature and salinity is very significant as ion exchange is reduced at extremely low temperatures (Finstad et al. 1988). However, Johnsson et al. (1994) stated that *O.mykiss* were better able to acclimatise to seawater during winter when water temperatures were lower, although not extreme.

The speed of transfer is also important and a 4 - 7 d acclimation period in 50% seawater before exposure to full seawater is recommended by Uno (1989) for *O.mykiss* and other species of trout. This may simulate the “natural” movement of some trout species into seawater, rather than acute changes in salinity caused by the immediate movement of fish from freshwater to seawater. However, changes in salinity has been used to treat external parasites of *O.mykiss*. For example, in an experiment at the SWFRAC in 1986, N. Morrissy and B. Jones (pers. comm.) increased the salinity of two groups of *O.mykiss* (n=10 and n=500) from 0 ‰ to 30 ‰ within 2 and 8 hours, respectively, in order to treat mycobacteriosis infections. The salinity was maintained at 30 ‰ for 2 and 6.5 hours, respectively, before being returned to 0 ‰. The rapid changes in salinity did not control the mycobacteriosis infections but the mortality rate due to salinity change was low, approximately 12 % and 2.5 %, respectively.

In terms of a tolerance range to salinity, both *O.mykiss* and *S.trutta* appear to be able to cope with salinities between 0 - 35 ‰. However, as most experiments were performed on older fish (e.g. 3 year old *O.mykiss* (Belkovskiy et al. 1991); 17 month old *S.trutta* (Galbreath and Thorgaard (1997)), the salinity required for young stages and successful reproduction are unknown although most species of salmonids target freshwater for redd building, successful spawning and as habitats for early life-stages. The feeding of high salt diets (up to 12% NaCl by dry weight, compared with the normal diet of approximately 1.4% by dry weight) to *O.mykiss* increased the survivorship during gradual and chronic transfer from freshwater to seawater (Salman and Eddy 1990). That experiment involved fish in three weight ranges between 10 - <40 g, with the largest increase in salinity tolerance in salt-fed fish greater than 20 g in weight (Salman and Eddy 1990).

Of particular interest is the performance of triploid hybrids in relation to salinity. Galbreath and Thorgarrd (1997) grew *S.salar* x *S.trutta* triploid hybrids and recorded significantly larger fish compared to diploid *S.salar* after a year of salt-water culture. Further, hybrids of wild and hatchery strains of *O.mykiss* displayed a reduction in seasonal fluctuations to sea-water tolerance (Johnsson et al. 1994), indicating a better fitness of the hybrids towards seawater. However, ploidy alterations have been recorded in *O.mykiss* embryos exposed to saltwater between the 2 - 8 cell stage (Miller et al. 1994). Thus, salinity may be an important consideration for the stocking and life-stage of release, and for the production of any self-sustaining population of trout in the south-west of WA, as although adult trout are euryhaline, reproduction and early stages require freshwater.

2.3 pH

The pH tolerances of trout have also been extensively tested due in part to the acidification of water bodies in the Northern Hemisphere. As a result, the tolerance to acidic waters (low pH) are often stated with little information about tolerances to alkaline waters. Although acidic freshwater bodies are present in WA, ranging from slightly acidic (e.g. pH 6.5, Lefroy Brook, Pemberton (J. Blaxell, pers. comm.)), pH 4.4 in Merridan (George and Frantom (1990) in Nulsen (1999) and pH 3.3 - 4.0 (mining voids in the Collie Coal Basin (Laurie 1998)), alkaline water bodies are also present in the south-west.

The results of a range of experiments have been reported for *O.mykiss* and *S.trutta* in waters approaching a pH of 4.5. In general, it appears that *S. trutta* are better at surviving in acidic waters than *O.mykiss* (Runn and Milbrink 1977; Edwards 1978; Grande et al. 1978) with Ikuta et al. (1992) recording 24 h LC_{50} of pH 3.83 for *O.mykiss* and pH 3.63 for *S.trutta*. However, a more recent study has tested *O.mykiss* at pH 3.25-4.0 with the conclusion that *O.mykiss* were tolerant to low pH, although the study was more directed at gill morphology and ion balance rather than survival (McDonald et al. 1991).

The overall results suggest that survival of trout is possible at pH values below 5.0. However, this has been mainly tested in adult or juvenile trout. However, it appears that tolerance to low pH is not well developed in early trout stages (e.g. egg or fry stage). For example, Thomsen et al. (1988) concluded that low pH (pH: 4.5 - 5.5) resulted in low hatching success of *O.mykiss* eggs, while Daye (1980) recorded no survival of embryos and alevins of *O.mykiss* in waters of pH 4.3 and below. Similarly, Barlaup et al. (1996) recorded survivorships of less than 1.0 % of *S.trutta* embryos in waters with pH 4.0-4.8.

Although able to cope with a range of pH, there seems little evidence to suggest that trout can be selectively bred to be more tolerant of low pH (Audet and Wood 1988). In contrast, Battram (1990) stated that pH tolerance may be slowly accumulated over several generations. Long-term sublethal effects due to pH (e.g. reduced growth and reproduction) have been suggested (Neville 1979) although rarely shown. Thus it appears that there needs to be more research directed on the pH tolerances of trout at all life stages, especially towards investigating sub-lethal effects.

In comparison to the effects of acidic waters on trout survival and culture, there are few studies examining the tolerance of trout to alkaline waters (high pH). As some areas of WA have naturally alkaline waters, information on the tolerance of trout to high pH is required.

In one of the few studies examining the effects of high pH on trout, Edwards (1978) stated that pH > 9 can kill salmonids, especially in the sensitive egg and early fry stages.

2.4 Dissolved oxygen

One of the most critical factors in determining trout survival is the level of dissolved oxygen in the water. For many species of salmonids, exposure to low levels of dissolved oxygen (less than approximately 5.0 - 6.0 $mg.L^{-1}$) can result in mortality (Doudoroff and Shumway 1970, in Weithman and Haas 1984). Oxygen concentration has been identified as the critical factor for the survival of *O.mykiss* from spawning to hatching (Rubin 1998).

Although *O.mykiss* have been recorded in a range of dissolved oxygen levels (2.6 - 8.6 $mg.L^{-1}$ (Thurston et al. 1981), <1.0 - 5.0 $mg.L^{-1}$ (Matthews and Berg 1997)), sub-lethal effects have been recorded in *O.mykiss* and other salmonids at moderate levels of dissolved oxygen. For example, the distribution of adult *O.mykiss* was observed to be restricted to areas where dissolved oxygen concentrations were above 2.5 $mg.L^{-1}$ (Rowe and Chisnall 1995). Morrison and Piper (1988) recorded a reduction in growth rate in *Salmo salar* fingerlings when dissolved oxygen levels were below 4.9 $mg.L^{-1}$. Similarly, MacConnell (1989) recorded a reduction in growth rates when dissolved oxygen content fell below 4.0 $mg.L^{-1}$ in fingerling Lake trout (*Salvelinus namaycush*), while Soderberg et al. (1983) stressed the importance of maintaining dissolved oxygen levels above 5.0 $mg.L^{-1}$ for optimum growth of small *O.mykiss* (55 g wet weight). Mortalities due to asphyxiation have been recorded in *O.mykiss* in waters with a dissolved oxygen concentration of 4 $mg.L^{-1}$ or below (Mathias and Barica 1985) and no hatching of *O.mykiss* eggs was recorded in oxygen levels below 4.1 - 8.7 $mg.L^{-1}$ (Miller 1989).

Several studies have indicated that dissolved oxygen levels have important synergistic effects. For example, higher oxygen levels reduced fish mortality due to parasites in *O.mykiss* (Yamamoto and Iida 1994; Caldwell and Hinshaw 1995). Yamamoto and Iida (1994) also recorded a significantly lower rate of oxygen consumption and more activity in triploid *O.mykiss* as compared with diploid fish at low oxygen levels (1.6 $mg.L^{-1}$). This suggests that selective breeding may identify a genetic basis for tolerance of trout to low oxygen levels in at least *O.mykiss*. This would have significance in WA as the oxygen carrying capacity of water declines rapidly as water temperature increases. Thus, a strain of trout tolerant to high temperatures and/or low oxygen levels would be ideally suited to inland saline culture of trout in WA.

In one of the few field studies examining dissolved oxygen effects on salmonids, Weithman and Haas (1984) correlated catch rates of *O.mykiss* with dissolved oxygen concentrations of lake water. Although fish were captured under a wide range of dissolved oxygen concentrations (2.6 - 13.0 $mg.L^{-1}$), capture rates of trout were reduced by 0.1 $fish.h^{-1}$ (approximately a 20% reduction in CPUE) for each 1.0 $mg.L^{-1}$ reduction in dissolved oxygen concentration between 2.4 - 6.0 $mg.L^{-1}$. Thus, dissolved oxygen concentrations play an important role in trout survival, distributions and fishery health.

It should be noted that many species of salmonids, including *O.mykiss*, can survive a wide range of salinities (Barton 1996). Further, some species of salmonid undergo a lifetime migration involving hatching in freshwater, migration to seawater and a subsequent return to freshwater to spawn. During these types of migrations, the temperature, salinity and dissolved oxygen content of the ambient water varies dramatically. This is due to the differential solubility of oxygen, being much lower in seawater than in freshwater, and much lower in warm water than in cool water (Schmidt-Nielson 1991). As a result, the risk of low dissolved oxygen levels to trout will increase as water temperature and salinity increases.

2.5 Ammonia

Ammonia is the most common form of nitrogenous waste produced by fishes. Toxicity of ammonia depends on the amount of un-ionised ammonia present, which in turn depends on the pH, temperature and salinity of the water (Table 1). In natural situations, ammonia may not be problematic to fish growth as it can diffuse through large water bodies and has a reduced toxicity in neutral or acidic waters (Barton 1996). Under intensive culture conditions or in highly alkaline waters (pH >9), ammonia may have sub-lethal effects, such as a reduction in growth rate, or may be acutely toxic (Stickney 1991) at total ammonia levels above 0.02 mg NH_3.N. L^{-1} (Hellawell 1986). Ammonia problems may also be prevalent in rivers and dams where ammonia is used as a fertiliser in catchment areas (e.g. agricultural areas). Ammonia is usually measured (as NH_3-N), and nitrite (NO_2-N) are the most toxic nitrogenous compounds to fishes. Nitrite is rare in natural waters as it is converted to nitrate (NO_3-N) by bacterial breakdown (Stickney 2000). Nitrate is far less toxic than ammonia, with nitrite being the most toxic nitrogenous compound to fishes in freshwater (Westin 1974).

Unlike many other compounds, ammonia becomes more toxic in alkaline waters. This is due to the de-ionisation of the more inert form of ammonia (ammonium - NH_4^+) to the highly toxic form (NH_3) in alkaline waters (Barton 1996), especially above pH 8 (Stevensen 1987; Stickney 1991). The exposure of fish to ammonia can have sublethal effects or can be acutely toxic. Exposure to sub-lethal doses affects the gills and may predispose fish to higher rates of bacterial infections, especially in poor quality water (Stevensen 1987). The 96 hour LC_{50} for ammonia (concentration where 50% of fish will die after 96 hours of exposure), as NH_3, is typically approximately 1.1 mg.L^{-1} for most species of freshwater fishes (Russo and Thurston 1991). In acute toxicity tests, 24 hour LC_{50} for ammonia (NH_3-N) were between 0.07-0.39 mg.L^{-1} for *O.mykiss* (Russo et al. 1974, Solbé and Shurben 1989) and 0.28 mg.L^{-1} for *Salmo salar* (Hellawell 1986), a close relative of *S.trutta*.

Although there is no direct information for *O.mykiss* or *S. trutta*, reductions in growth rates have been recorded in other salmonids when ammonia levels increased to 0.4 mg.L^{-1}. Morrison and Piper (1988) and MacConnell (1989) both recorded reductions in growth rates due to ammonia levels in *Salmo salar* (0.40 mg.L^{-1}) and *Salvelinus namaycush* (0.75 mg.L^{-1}) respectively. However, both studies were confounded as both ammonia levels increased and dissolved oxygen levels decreased, simultaneously. Further, although ammonia may have a direct effect on growth and/or survival, increased levels of ammonia may also have indirect effects. For example, Soderberg et al. (1983) recorded increasing mortalities with increasing (unionised) ammonia concentrations in *O.mykiss*. However, all fish that died during the 120 day experiment had a parasitic epizootic infection. Thus, Soderberg et al. (1983) concluded that high ammonia levels may predispose *O.mykiss* to infection, rather than killing the fish directly. Bosawowsky and Wagner (1994) recorded that fin-erosion was significantly correlated with the levels of unionised ammonia in an intensive culture situation involving both *O.mykiss* and *S.trutta*.

It is generally recommended that the level of ammonia as NH_3 be kept below 0.01 $mg.L^{-1}$ (DFO 1973 in Barton 1996) and 0.0125 $mg.L^{-1}$ (Piper et al. 1982) for successful salmonid culture. This can be achieved by keeping pH < 7.0 (Stickney 1991) or pH 8.0 (Stevensen 1987) or providing aeration in alkaline waters (pH 8.0 - 8.5) (Stickney 1991).

2.6 Water hardness

Water hardness is the total of calcium and magnesium "salts" (ions) measured in the culture water (Wedemeyer 1996) but can generally be thought of as the total calcium carbonate ($CaCO_3$) concentration of the water, in at least waters with low or zero chlorine levels. Water hardness is an important consideration in salmonid culture due to the effects of water hardness on the solubility of other ions. For example, in contrast to ammonia, many other ions including copper and zinc can enter fish in toxic amounts via the gills (Bradley and Sprague 1985; Anadu et al. 1989; Wedemeyer 1996), especially as the pH of the water decreases (becomes more acidic) (Wedemeyer 1996). Further, many ions become unavailable to fish in low pH waters. As a result, fish need to spend a great deal of energy, up to 3% of their total needs (Wedemeyer 1996), to keep their ion levels in balance. To avoid the toxicity of ions in "soft" waters, water should be relatively hard (i.e. calcium carbonate ($CaCO_3$) levels greater than 200 $mg.L^{-1}$) (Barton 1996; Wedemeyer 1996).

Keeping water hardness at a suitable level has a number of benefits in trout culture including;

- Reducing the toxicity risks of most ions (e.g. zinc, copper);
- Buffering highly acidic waters.
- Reduction in disease risks (Wedemeyer 1996).

Hardness can be easily measured and can be regulated by the addition of inexpensive sources of $CaCO_3$, including agricultural lime and limestone.

2.7 Synergistic interactions

Although the above briefly outlines the effects of a single variable, it should be noted that the cumulative effects of interactions between and among variables (synergy) is an important concept, as many variables will influence fish growth and survival at any moment in time. For example, increasing water temperature will not only affect trout directly, but will also reduce the oxygen carrying capacity of the water as well as increasing the oxygen demand of fishes. This interaction between temperature and oxygen carrying capacity is particularly important if burst swimming occurs or if trout have been recently fed at high temperatures, as the post-prandial specific dynamic effect can lead to a major increase in oxygen demand (Driedzic and Hochachka 1978). Thus any responses by fish to temperature may be due to temperature, or dissolved oxygen levels, or the synergistic response due to both variables, or another, unmeasured variable. Similar to the relationship between water temperature and dissolved oxygen levels is the synergy between ammonia concentrations and dissolved oxygen levels; increases in ammonia concentrations will often result in a decrease in the dissolved oxygen levels (Hellawell 1986) as a result of the breakdown of organic matter.

The concentration of ammonia in the form of NH_3 is also affected by water temperature, pH and salinity. Although ammonia concentration is usually measured as total ammonia (the sum of NH_4^+ and NH_3) the ratio of non-toxic NH_4^+ to the potentially toxic NH_3 varies dramatically (see table 1). In brief, ammonia toxicity is reduced in neutral or slightly acidic (pH 6.0 - 7.0) freshwaters. As the pH rises, (becomes more alkaline), the proportion of toxic NH_3 rises and can cause health problems and mortalities. Increases in water temperature will also compound the problem by converting more NH_4^+ to NH_3. However, this temperature effect is somewhat reduced in saline waters (Wedemeyer 1996).

Table 1. Contribution by NH_4+ and NH_3 to total ammonia levels at different combinations of pH, temperature and salinity. (* Data from Emerson et al.(1975); # Data from Wedemeyer (1996)).

pH	Temperature (ºC)	Salinity (º/ºº)	Percent of total Ammonia as NH_3 (toxic)
7.0*	0	0	<1
9.5*	0	0	21
9.5*	30	0	72
7.4#	20	0	<1
7.4#	20	28-31	0.8
9.0#	20	0	28.4
9.0#	20	28-31	24.5

A major outcome of this review is that there are very few reports detailing the results of experiments in which a single variable is altered while all others are held constant. However, it should be noted that as many of the articles deal with trout culture situations, the response to a major variable (like temperature) is important, not the biological reasons for the response. For example, temperature stress impacts on the osmoregulation capabilities of fishes and thus water salinity and environmental calcium concentrations will impact on survival at temperature extremes (Boyd and Tucker 1998).

Nonetheless, the processes by which trout respond to a variable may provide further insight into the ecological or biological responses in these species, and in turn yield information pertinent to culture situations. A relevant example from Western Australia is the incidence of *Mycobacterium marinum* infection on *O.mykiss* populations at the SWFRAC, Pemberton. While under most conditions, the rate of *M.marinum* infections is negligible, once the water temperature exceeds 25 ºC, the rate of infection increases dramatically and high mortalities have been recorded (T. Church and B. Jones, pers. comm.). The management of *M.marinum* is simply controlled at the SWFRAC by turning-on evaporative cooling water towers fitted to all trout ponds when the water entering the ponds exceeds approximately 23 ºC. Extreme temperatures not only increase infection rates but also alter water chemistry. For example, it can be difficult to separate the effects of temperature from changes in free carbon-dioxide concentration, presence of anions and cations in solution and the precipitation of ions (such as iron) in ion-rich water.

3.0 Toxins: Trace metals, heavy metals and poisons

A range of studies have evaluated the effects of various metals and toxins on trout (Table 2). These have been aimed at establishing the suitability of degraded rivers for trout use or for the effects of specific compounds on trout. Many of the rivers of the south-west of WA will be free of most of these compounds, and/or the information on presence of these compounds in these river systems is absent. However, waters from mine sites and underground sources being considered for trout culture may contain unusual concentrations of trace ions and heavy metals. The testing of source water is strongly recommended as the starting point for any aquaculture venture.

Typically, many of the studies involving the tolerances of trout have involved individual metals in waters of differing pH and hardness. The experiments usually target the effect of elements under low pH conditions, a typical environmental condition due to acidification of northern temperate streams through industrial pollution (see Mance (1987) for examples).

Overall, many of the metals tested have had little effect on egg and fry survival. For example, Sayer et al. (1991) tested the effects of a range of heavy and trace metals on fertilised ova (aluminium (Al), copper (Cu), lead (Pb), and zinc (Zn)) and yolk-sac fry (manganese (Mn), iron (Fe), nickel (Ni), cadmium (Cd) with and without Al and Cu) of *Salmo trutta*. Most experiments recorded moderate trout mortalities (0-22%) except in mixtures containing Al or Cu (31 - 72% mortality) or Cu and Fe (78% mortality). However, mortalities could be reduced with the addition of lead and /or zinc (Sayer et al. 1991).

Other authors have tested the effect of fewer metals but with similar results. Miller et al. (1993) tested the effect of dietary (13 - 684 $mg.kg^{-1}$) and waterborne (5 - 106 $\mu g.L^{-1}$) copper and found no significant effects on growth, condition, mortality or food conversion efficiencies in older *O.mykiss*. Similarly, Lanno et al. (1985) recorded no effect on feeding efficiency by older *O.mykiss* with diets containing 664 $mg.kg^{-1}$ of Cu, however, diets containing 730 $mg.kg^{-1}$ Cu induced mortalities. Further, sub-lethal doses of Cu resulted in higher levels of Fe and Zn being taken up by the fish, suggesting an electrolyte imbalance, with possible sensitisation to Zn due to copper exposure (Hellawell 1986). Although few significant effects of metals have been recorded in trout, both Miller et al. (1993) and Lanno et al. (1985) concluded that the effects of dissolved or waterborne Cu were much greater on fish growth and health than dietary Cu. Further, the effects of exposure to high (12.5 $\mu g.L^{-1}$) levels of waterborne Cu may be reversed if fish are transferred to clean (Cu-free) water and held there for several days. This is most likely due to the immediate impact of waterborne metals as they enter the fish across the gill membranes and are immediately available to the fish via the bloodstream, whereas dietary metals must be engulfed, digested and absorbed before becoming available to the fish. Although the concentrations of Cu required to cause mortalities are relatively high, the toxicity of Cu increases dramatically in “soft” water (Hellawell 1986). It should also be noted that trout may be exposed to different sources of Cu, for example in algicides used for fish and animal husbandry (copper sulphate (Mance 1987)).

By far the most research on metal tolerances in trout has been with aluminium (Al). The reason that Al has been widely tested for is due to the bio-availability of Al in waters with pH less than 7, a common situation in degraded rivers in northern Europe. It is also likely that at least some rivers in south-western Western Australia may contain high concentrations of Al due to the large deposits of bauxite (aluminium ore) within many south-western catchments. Aluminium causes immediate effects on trout including micification (over production of mucous on the gills) and "coughing". These effects occur in acidic waters as the electrolyte movements out of the gills causes a slightly negative charge to form at the gill filament surface, resulting in the deposition of Al ions on the gill membranes. To combat this, fish produce mucous to "slough-off" Al build-up, resulting in micification. As the efficiency of gas exchange is reduced under these conditions, the fish may increase ventilation rates by increasing the rate of opercula movement, resulting in the appearance of "coughing". Again, these effects may be mitigated by moving fish to clean water or waters with a neutral pH (Dietrich et al. 1989).

Interestingly, different stocks of *O.mykiss* have been recorded as having vastly different susceptibilities to metal contamination (Roch and McCarter 1984) suggesting a genetic basis for metal tolerance. Resistance to at least aluminium has been recorded for *O.mykiss* exposed to high levels (118 $\mu g. L^{-1}$, pH 5.2) for long periods of time (Reid et al. 1991). However, sub-lethal effects (reduction in liver size and function, changes in the endocrine system) were recorded in *O.mykiss* adults and juveniles exposed for long periods (30 days) of high cadmium concentrations (1, 5, 10 and 25 Cd $\mu g.L^{-1}$) with no signs of increased resistance at lower concentrations (Ricard et al. 1998).

Although widely studied, the effects of metals and environmental tolerances are often measured by monitoring LD_{50} effects. That is, fish are exposed to a set of conditions and the time until 50% of the test fish have died is recorded. These acute-type measurements are very widespread in many fields (e.g. effect of oil spills etc) and provide very quick results as most experimental time periods are only up to 96 hours (Thurston et al. 1981; Ferguson and Hogstrand 1998). However, very few experiments have examined the long-term (chronic) or sub-lethal effects of exposure to metals or other variables.

Table 2. Summary of experiments evaluating the effects of some compounds or elements on salmonids. More information is available in Mance (1987).

Species Compound	Element or	Concentration	Results	Comments	Source
O.mykiss	Aluminium	0-400 µg.L^{-1}	Higher mortality rate with higher aluminium concentrations and lower pH	pH 5.2-5.6; 96 h experiment.	Dietrich and Schlatter, 1989
		0 - 71 mg.L^{-1}	Exposure to aluminium reduced survival.	pH 3.6 - 7.7; 25 day experiment.	Thomsen et al., 1988
O.mykiss	Cadmium	0 - 5.0 µg.L^{-1}	Increased concentrations increased mortality rate. Temperature may also increase susceptibility.	Embryos and larvae in LC50 trail.	Dave et al., 1981
O.mykiss	Copper	0-684 mg.kg^{-1}	Little difference in growth, mortality or condition.	42 day study; Feed and waterborne copper	Miller et al., 1993
		0 - 730 mg.kg^{-1}	Maximum dietary level of 665 mg.kg-1 before mortality	Copper in food; copper accumulation in liver;	Lanno et al., 1985
		55 µg.L^{-1}	Reduced sodium levels and uptake for first 7 days	24 week experiment. Copper affects the permeability of the gills, making ion balance and transition between waters of differing salinities more difficult; 28 day experiment.	Lauren and McDonald, 1987
O.mykiss	Zinc	0.1 - 10.0 mg.L^{-1}	Low pH and high hardness reduced the effects of zinc.	pH - 5.5 - 9.0; Hardness - 30 - 40 mg $CaCO_3$.L^{-1}. 120 hour tests	Bradley and Sprague, 1985
		3.01 µg.L^{-1}	Mortalities	Histopathological changes to gills and kidneys	Dept. of Fisheries, Fish Health record, B. Jones pers.comm.

S.trutta	Trace Metals	Aluminium - 6000 nmol.L^{-1} Copper - 80 nmol.L^{-1} Lead - 50 nmol.L^{-1} Zinc - 300 nmol.L^{-1} Manganese - 1500 nmol.L^{-1} Iron - 2500 nmol.L^{-1} Nickel - 200 nmol.L^{-1} Cadmium - 4 nmol.L^{-1}	High mortalities in aluminium and copper treatment, and copper and iron treatment; Copper more toxic than aluminium; Lead and zinc in a solution reduced the toxicity of aluminium and copper.	All combinations of trace metals were tested; 300 degree-day period (days x degrees °C).	Sayer et al., 1991
S. salar; Salvelinus namaycush	Ammonia (NH_3-N)	2.3-8.4 μg.L^{-1}	Higher ionised ammonia concentrations reduced growth and survival, through epizootic infection	120 day experiment	Soderberg et al., 1983
			Increasing mortality with increasing concentration ; Salt did not protect fry stage but did protect smolts.	96 hour experiment	Soderberg and Meade, 1992
O.mykiss (young)	Sumithion (Insecticide)	12.8-42.4 ppm	Higher temperatures resulted in higher mortality rates	Temperature between 7.7 - 20.6 °C	Hashimoto, 1985
	Cypermethrin	1.4-2.52 μg.L^{-1}	LC_{50} values	12 -96 hour experiments, fry and juvenile fish	Davies *et al.* (1994)
	Alpha-	5.6 - 350 μg.L^{-1}	LC_{50} values	96 hour experiment, fry	Shires (1983) in WHO (1992)]
	cypermethrin	10 - 71 μg.L^{-1}	LC_{50} values	96 hour experiment, ova	Pearson (1986) in WHO (1992)]
Salmo clarki henshawi	UVB Radiation	Not applicable	After 48 h sunburn and necrosis had occurred	72 hour experiment	Blazer *et al.*, 1997

4.0 Sub-lethal effects

It is likely that adverse sub-lethal effects do occur. For example, in south-western Western Australia, *S.trutta* and *O.mykiss* have been released into natural waterways for at least 60 years. Although adult trout are targeted in recreational fishing, very few populations are self-supporting and restocking needs to be done on an annual basis. This is most likely due to the lack of many areas suitable for redd formation, and thus, the population is not self-sustaining due to the lack of a single feature (suitable gravel beds) at a single life stage (spawning adult) and thus, the life-cycle is interrupted. Although a simple example, the effects of sub-lethal responses may occur for a variety of other biological parameters. Many fish have a very tight requirement for salinity for survival or reproduction. One example, is the black bream *Acanthopagrus butcherii* which is targeted by recreational fishers even in upstream areas (Molony 2000). Although *A.butcheri* will tolerate low salinity water for extended periods of time, the effects of low salinity (< 3 ‰) and low winter temperatures results in mortality (Maguire and Sarre 1999). Similarly, a tropical black bream, *A.berda*, will live under a wide range of salinities (0 - 45 ‰, Sheaves 1996) but will only successfully reproduce in salinities between 22-34 ‰ (Molony and Sheaves 2001). Although both *S.trutta* and *O.mykiss* are able to survive under a range of environmental conditions, it is likely that both species will possess a narrower range of a variable that will produce optimal growth and survival. The long-term sub-lethal effects (e.g. growth rates, condition) should be quantified and monitored in relation to water parameters, especially in commercial culture situations.

5.0 Environmental requirements for trout in rivers and streams

Besides correct physical water conditions and chemistry, certain environmental parameters of streams and rivers are required for survival, growth and therefore successful stocking of trout. Little is known about the habitat and environmental requirements of trout in south-west of Western Australia as both *O.mykiss* and *S.trutta* are introduced species and have negligible reproduction in many of the waters in WA and have thus been annually stocked for several decades. However, previous studies in rivers and streams of North America and Europe have identified specific factors that account for high levels of variations in trout abundances and growth rate (Ekloev 1996; LaVoie and Hubert 1996; Baran et al. 1997; Danehy et al. 1998; Greenberg and Dahl 1998) or the likely impacts of habitat modifications (Huusko and Yrjaenae 1997; Kelly and Bracken 1998). For example, in two studies dealing with *Salmo clarki bouvieri* (closely related to *O.mykiss*) in North America, Binns and Eiserman (1979) and Varley and Gresswell (1988) identified nine variables that explained over 90% of variation in standing stocks of self-recruiting populations of this species;

1. **Late summer stream-flow:** The flow at the end of summer should be high enough to support maximal trout numbers. An approximate calculation was used where average daily late summer flow needed to be greater than 55% of the average daily flow rate for the year. That is, perennial streams were preferred by trout.

2. **Annual stream-flow variation:** Trout seemed to prefer little or no variation in flow rate throughout the year. The "worst" trout streams were intermittent.

3. **Water velocity:** The study showed that the highest trout densities were found in the fastest flowing waters (based on volume throughput estimates of individual streams). The highest trout densities were recorded in water velocities of 45.6 – 76.0 $cm.sec^{-1}$. However, trout have also been recorded in high abundance in water speeds exceeding 156-321 $cm.sec^{-1}$ (Varley and Gresswell 1988).

4. **Trout cover:** Cover, defined as sheltered areas in a stream where trout can rest or hide from predators (i.e. snags, logs, undercut banks, large rocks, etc), was positively correlated with trout abundance. The best trout areas had in excess of 55% of the available area of the stream containing some form of cover. The most inadequate streams still had cover, but less than 10% of the area of a stream.

5. **Stream width:** Stream width did not exhibit a linear relationship with trout abundance. The worst streams for trout were very narrow (less than 0.6 m) or very wide (greater than 46 m). The best streams for trout were between 5.4-6.6 m wide and is probably a function of the ratio of stream width to cover available (i.e. the relative area of overhanging banks).

6. **Eroding stream banks:** The presence of eroding banks (expressed as a percentage of total bank length) was also highly correlated with trout density. The highest abundances of trout were found where little or no erosion was evident (0-9%). Most erosion of riparian banks in Western Australia is due to inadequate management practices, including allowing cattle to access and wade through streams (pot-holing).

7. **Stream substrate:** In this instance, the substrate referred to the presence of aquatic vegetation (including macro-algae and moss) which was indicative of the amount of

aquatic food (e.g. insect larvae) available to the trout (Binns and Eisermann 1979). The more abundant macro-algae was at a site, the more habitat for food items and thus the higher the density of trout. This should not be confused with the substrate in terms of sediments or gravel required for trout reproduction.

8. **Nitrate-nitrogen concentration (NO-N):** Most trout were recorded in areas with moderate nitrate nitrogen concentrations (0.15 - 0.25 mg.L^{-1}). At low levels (<0.001 mg.L^{-1}) or high levels (>2.0 mg.L^{-1}) fewer trout were recorded. Nitrogenous compounds are often limiting in freshwaters and thus higher levels would result in higher productivity, more food items and therefore more predators, including trout. However, very high concentrations, particularly combined with low pH and high temperatures, results in eutrophication and may limit oxygen levels or act as a direct toxin to trout, especially in the form of nitrite (NO_2) or ammonia (NH_3) (see ***Ammonia*** section above).

9. **Maximum summer water temperature:** Moderate maximum summer water temperatures were the best for trout density (12.6-18.6 °C) with very few trout recorded in areas with maximum summer water temperatures less than 6 °C or greater than 26.4 °C in North American streams.

Although these studies were performed on self-reproducing populations of trout, the factors are likely to be important in non-self reproducing populations of trout in WA to maximise carry capacity of a particular waterbody and survival and growth of trout.

It should be noted that as electro-fishing was the preferred sampling technique in the above studies, biomass estimates are likely to have been biased by large fish which are more prone to electro-fishing (Reynolds 1996). Further, electrofishing can only be used in some areas, generally small streams and headwaters (Reynolds 1996). Thus, the actual numbers and biomass of fish within an area are unlikely to be known precisely. However, in another electrofishing study on salmonids, Binns and Eiserman (1979) did state that, besides trout, they also collected whitefish (*Coregonus* spp), suckers (*Catostomus* spp), minnows (*Hybognathus* spp) and/or sculpins (*Cottus* spp). As some of these species of fishes are relatively small (down to approximately 10 cm TL) as adults, small-sized trout may have also been collected. However, very small fish are likely to be missed by electrofishing (Reynolds 1996). Further, there is a growing body of literature that documents damage to fish, especially salmonids, due to electrofishing (Hollender and Carline 1994; Nielson 1998).

Despite the potential short-comings of sampling in some salmonid ecological studies, it is likely that similar variables could be identified explaining differences in abundance and growth rates of both species of trout in south-west WA. It should be noted that some of the variables in the studies by Binns and Eiserman (1979) and Varley and Gresswell (1988) may vary in Western Australia. For example, the distribution of trout in relation to water temperature may show that WA fish have a higher tolerance to environmental temperatures, as shown in research performed at the SWFRAC, Pemberton (Molony unpublished data). However, the studies by Binns and Eiserman (1979) and Varley and Gresswell (1988) could be applied in WA to either identify particular areas that possess favourable trout characteristics and would therefore be likely candidates for restocking one or both species of trout, or be used in habitat enhancement studies (augmentation) to modify (or restore) certain areas to make them more favourable for trout, and thus increase the number of fish, and thus fishing success, in a particular area.

6.0 Conclusion

Although salmonids in general, and *Salmo trutta* and *Oncorhynchus mykiss* in particular, are able to tolerate broad ranges of physical and environmental variables (table 3), their tolerance ranges may be breached in some circumstances in the south-west of Western Australia. In particular, maximum summer temperatures of Western Australian waters may exceed the critical thermal tolerance of both species (approximately temperatures greater than 25 - 26 °C). Thus, areas that are being considered to be stocked with trout should be assessed at least for annual maximum water temperatures before stocking is undertaken.

With this in mind, however, both *S.trutta* and *O.mykiss* possess the ability to inhabit a wide range of conditions and appear suitable for many of the water bodies in the south-west, including inland saline waters of the southern Wheatbelt, cool marine waters such as the Peel-Harvey estuary, areas of low pH and freshwater systems with or without traces of metals. However, it appears that *S.trutta* is slightly more tolerant to most environmental conditions than *O.mykiss*, although *O.mykiss* tend to grow faster, is more readily available in WA and has a greater CPUE than does *S.trutta* (Molony, unpublished data). Thus, a consideration of the species to be stocked and the objectives of the stocking program is required at the onset of any venture.

Further, improvements in tolerance may be made by selective breeding programs. Although developing tolerance is still questionable for some variables such as pH (Audet and Wood 1988), selective breeding to produce a more saline tolerant or heat tolerant strain appears feasible within a few generations. Current research at the SWFRAC by Department of Fisheries indicates that a heat tolerant strain of *O.mykiss* has developed after years of passive selection for temperature, within deliberate selection for faster growth. Genetic research on this strain is currently underway. However, further research on the tolerances of young stages (ova, fry and yearlings) should be undertaken to confirm the development of tolerances.

Table 3. Summary of requirements for the successful culture of trout.

Table 3a. Comparison of some requirements for growth (G) and survival (S) of trout as stated by some authors. The differences in the values of the requirements by the authors reflects differences among different geographical stocks. In general, both *S.trutta* and *O.mykiss* have similar requirements for all parameters. The major difference between brown and *O.mykiss* requirements in culture situations is that *S.trutta* require a lower temperature for high reproductive success (less than approximately 18 °C, pers. obs.).

Parameter	Sedgwick (1985)	Stevenson (1987)	Barton (1996)	Wedemeyer (1996)	Brannon (1991)
Temperature (°C)	10-15 (G) (best below 21, lethal >25-27 (S)	10-16 (G) (best below 20, lethal >25(S)	10-22 (G) (lethal >26.5 (S))		9-16 (G) (<26 (S))
Salinity °/oo			0-30 (S)		
pH	7.0-7.5 (G) (Not below 6.0 (S))	7.0-7.6 (G) (Not below 6.0 (S))	6.5-8.0 (G)	7.0-8.0 (G) (6.0-9.0 (S))	6.7-8.5 (G)
Dissolved Oxygen ($mg.L^{-1}$)				>7 (S)	7.0 (G)
Calcium (hardness) ($mg.L^{-1}$)	>150 (G)		10-400 (G)	50-200 (S)	>50 best (G) (4-160 (S))

Table 3b. Summary of the requirements for successful growth (G) and survival (S) of trout.

Parameter	Range	Source
Temperature (°C)	10-22 (G), >26.5 (S)	Barton (1996)
Salinity (°/oo)	0-30 (S)	Barton (1996)
PH	7.0-8.0 (G) (6.0-9.0 (S))	Wedemeyer (1996)
Dissolved Oxygen ($mg.L^{-1}$)	7.0 (G)	Brannon (1991)
Ammonia (NH_3-N $mg.L^{-1}$)	<0.0125 (G) < 1.8 (S)	Smith and Piper (1975) in Soderberg et al. (1983) Department of Fisheries, Fish Health record, B. Jones pers.comm.
Nitrite (NO_2-N $mg.L^{-1}$)	<0.000012 (G) <0.23 (S)	Westin (1974) Birkbeck (1973) in Brown and Mcleay (1975)
Nitrate (NO_3-N $mg.L^{-1}$)	< 0.025 (G) < 0.25 (S)	Westin (1974)
Calcium (hardness) ($mg.L^{-1}$)	>50 best (G) (4-160 (S))	Brannon (1991)
Zinc ($mg.L^{-1}$)	<3.01 (S)	Department of Fisheries, Fish Health record, B. Jones pers.comm.

Finally, although both species appear able to tolerate a wide range of aquatic conditions present in the south-west of Western-Australia, the carrying capacity of some water bodies may be relatively low due to the lower productivity of most WA waters in comparison with waters in the Eastern States and around the world. Increases in carrying capacity and the possibility of larger, self-sustaining populations, may be possible through enhancement of waterways to meet the ecological and dietary requirements of both species. This is a requirement for the successful intensive aquaculture of trout in purpose-built ponds and facilities, where feeding and pond-design are critical. However, any modifications to natural waterways (i.e. rivers) and irrigation dams should be carefully considered and evaluated for the effects on native fishes and invertebrates such as the marron (*Cherax tenuimanus*). Nevertheless, the fact that many south-west waterways are unsuitable for large-scale natural reproduction by *S.trutta* and *O.mykiss* may be exploited as a management tool in order to retain control of these introduced species, an option that is not available for other introduced freshwater fishes (e.g. redfin, *Perca fluviatilis* and carp, *Cyprinus carpio*).

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9.0 Figures

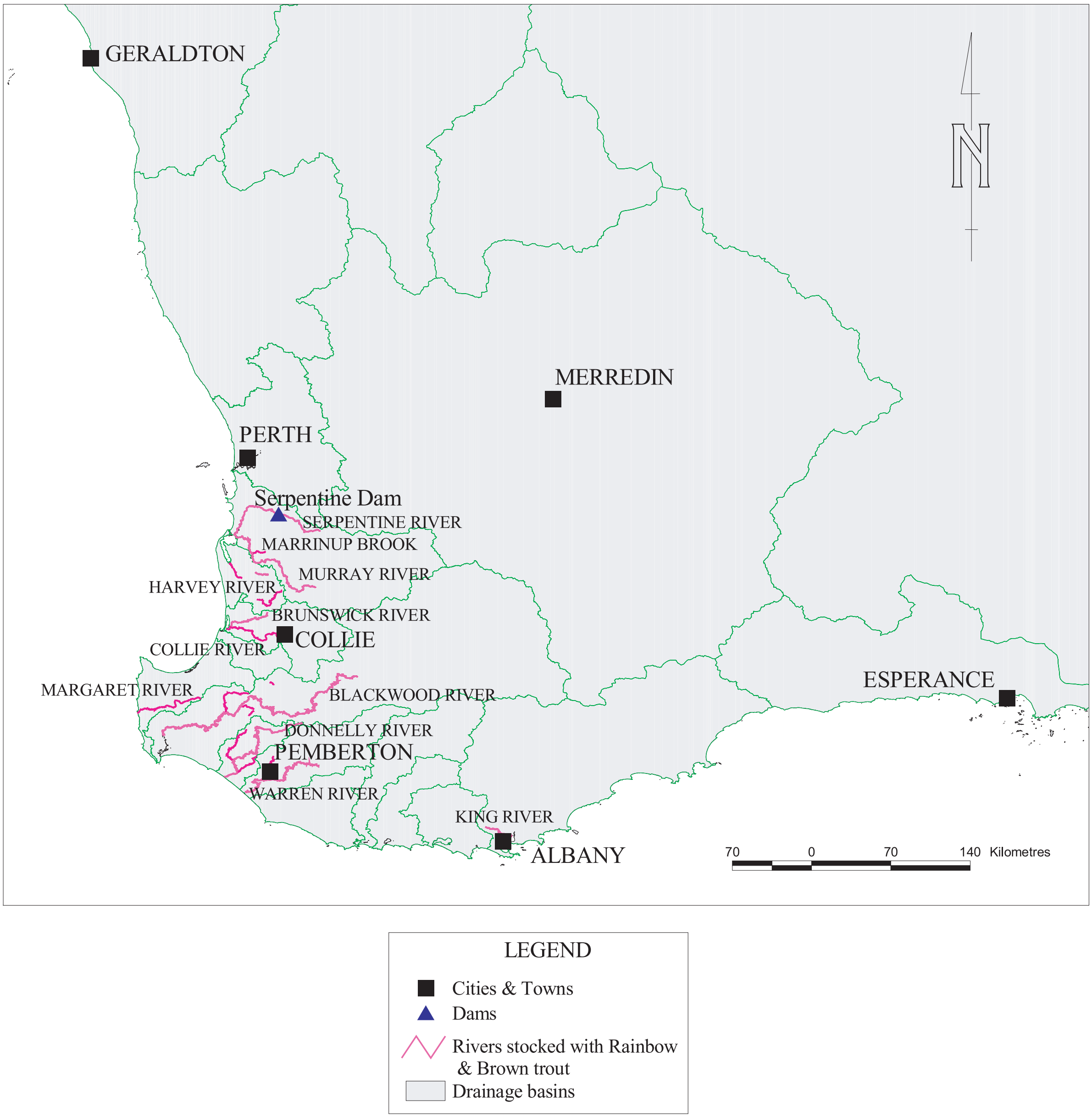
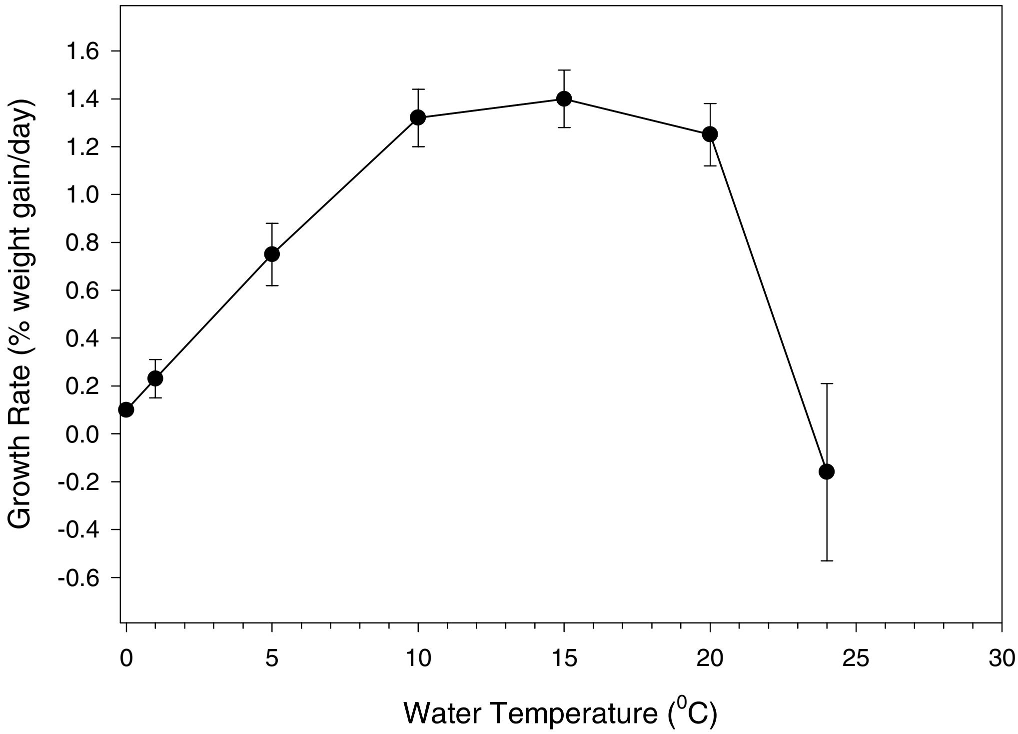


Figure 1. Map of the south-west of Western Australia identifying the current distribution of brown and rainbow trout stocking in rivers and dams by Department of Fisheries. Other locations mentioned in the text are also provided.

A



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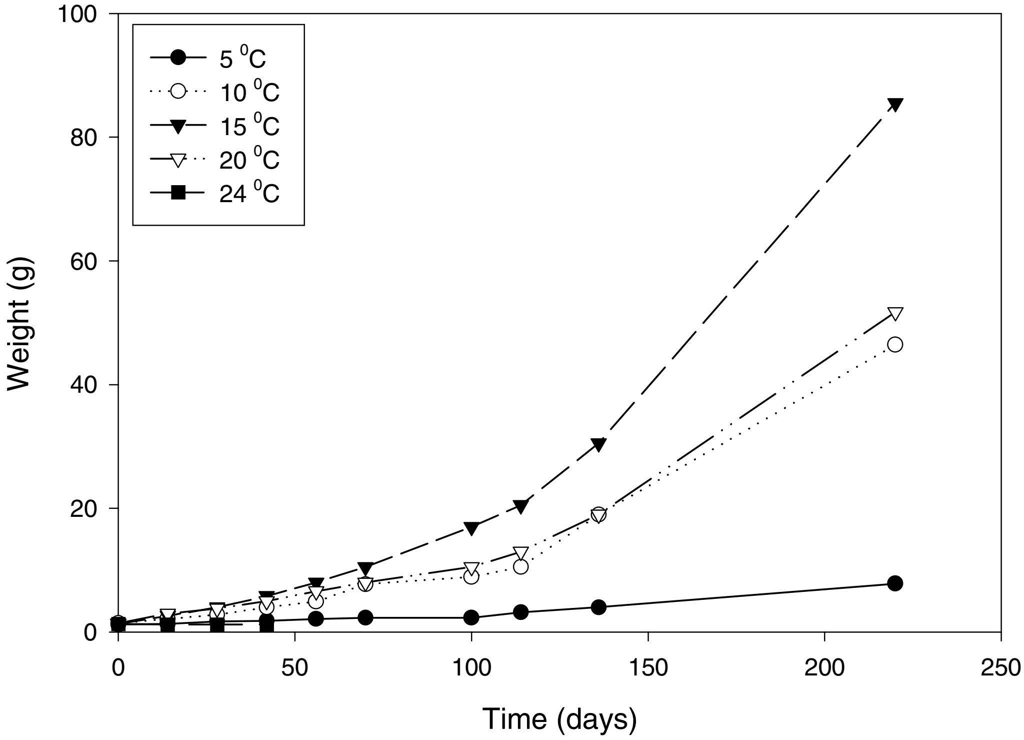

Figure 2. The effect of temperature on the growth of fingerlings of a generalised salmonid fish, *(Oncorhynchus nerka)* in freshwater (figures from Brett et al. 1969).

A). Growth rate as percent increase per day as a function of temperature.

B). Overall weight gain of fish reared at a range of temperatures. Figures redrawn from data presented in Brett *et al.* (1969). Note that these figures are based on Northern Hemisphere fishes where water temperature rarely exceeds 20 °C. It is expected that the WA strain of fish will display a similar pattern of growth but the optimum growth rate will be achieved between 20 - 24 °C.