

Electrofishing – Theory and practice with special emphasis on salmonids

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Abstract

This report attempts to establish guide-lines for electrofishing in population studies and is the result of literature studies and experience from electrofishing in Denmark, Finland, Norway and Sweden. Equipment, safety and training, sampling design and precision requirements for various types of investigations, population estimation and fishing practice are discussed. The results are put forward in the form of recommendations. Special attention is paid to the sampling design of surveys in streams of different types and for different purposes. Examples of the computation procedures are also included.

Introduction

The breakthrough of electrofishing in the 1950's and 60's opened new horizons for fishery biologists. Quantitative investigations of fish populations in running water, previously regarded as nearly impossible, were now within the realm of possibility. The electrofishing apparatus also permitted careful trapping of fish for later use in breeding, marking and release experiments. Electrofishing has also been carried out as a supplement to traditional trapping methods in lakes, mostly in areas near the shore. In this manner, the electrofishing gear has become a common tool for fishery biologists, and is today used by most

persons and institutions engaged in freshwater fish research.

In Nordic countries electrofishing is primarily used in running waters. Conflicts between fisheries and other interests are increasing at the same pace as the ever growing use of rivers and streams for drainage of agricultural, residential and industrial waste. Stream regulation and acidification have also increased the need for quantifying fish populations in running water.

Meanwhile, using electrofishing creates several problems. These are partially associated with a lack of 'biological' understanding (limited knowledge about how fish populations fluctuate in time and space), but are primarily attributable to the

fact that electrofishing is carried out by a variety of techniques with different kinds of equipment. Therefore applied usage of large amounts of electrofishing data previously collected is sorely limited.

In spite of electrofishing's many promising qualities (effectivity, simplicity, relative harmlessness for captured fish), we have today a much more limited knowledge of the relationships and the effects of environmental disturbance than would otherwise have been the case had electrofishing techniques been more uniform, with the precision and reliability of results better understood. Therefore, the goal of the present report is that future electrofishing methods as well as the processing of data shall conform to specific standards. A standardization of procedures used in different watercourses will result in comparable data, greater fishery biological understanding and an increased significance of results which may be useful in a variety of contexts.

This work started at the University of Oslo in 1981, at a meeting attended by the foremost authorities on electrofishing in the Nordic countries. The meeting concluded that an attempt at standardizing electrofishing in the Nordic countries was essential, and a resolution was made for the establishment of a small study group for further investigations. The group was composed of the following persons: Torgny Bohlin

(Sweden), Stellan Hamrin (Sweden), Tor G. Heggberget (Norway), Eero Juttila (Finland), Østen Karlström (Sweden), Albert Lillehammer (Norway), Jan Nielsen (Denmark), Gorm Rasmussen (Denmark) and Svein Jakob Saltveit (Norway). The leader of the work has been Tor G. Heggberget.

This work is largely based on 'Quantitative electrofishing for salmon and trout – views and recommendations' (Bohlin, 1984). We have, however, expanded the contents to include some of the most common situations in Nordic countries and elsewhere, regarding physical (water type, watercourse size) and biological (fish species, fish size) conditions.

Electric fishing in fresh waters: equipment and efficiency

Equipment

Electric fishing gear consists of three main parts, a power unit device (generator or battery), a transformer and electrodes (Fig. 1). The power unit generally produces alternating current and the effect of the unit determines the maximum voltage in the water. The transformer converts the original current to direct current of different voltage and produces the shape, length and frequency of the

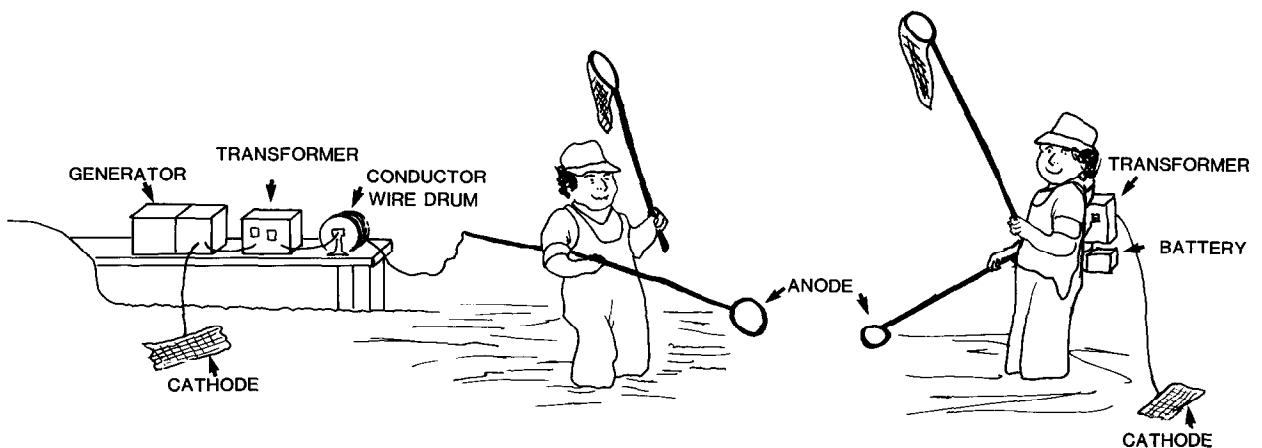


Fig. 1. Equipment used for electrofishing with stationary (left part) and mobile systems.

pulse. The shape of electrodes determines the field strength.

The power unit produces the energy required, which increases with the conductivity of the water. At low conductivity ($< 75 \mu\text{S}$) the voltage needed is acquired with an effect of less than 1 kW and both batteries and generators can be used. At higher conductivities batteries are too rapidly discharged and stronger power units must be used. At $500 \mu\text{S}$ the effect required is approximately 2 kW and in marine environments 5–10 kW (cfr. Hickley, 1985). Such devices are heavy but could be used for electric fishing as long as suitable means of transportation are available (Vibert, 1967; Sternin *et al.*, 1972; Weiss, 1972, 1976; Dembinski & Korycka, 1974; Cross, 1976;

Lamarque, 1977; Phillips & Scolara, 1980; Heidinger *et al.*, 1983). Even at conductivities typical for eutrophic lakes the effect needed causes problems with respect to weight and size of the power unit. Especially in this type of water, it is therefore essential to optimize the efficiency of transformers and electrodes. Most power units produce 2-phase alternating current, converted into some kind of direct current by a transformer. When using electronic devices high frequency ripple might arise, which may lower the efficiency (Priegel & Novotny, 1975). With other types of equipment a certain degree of pulse might remain when transforming to direct non pulsed current (Hartley, 1980). In the first case an electric filter could be used to reduce the ripple, while in the

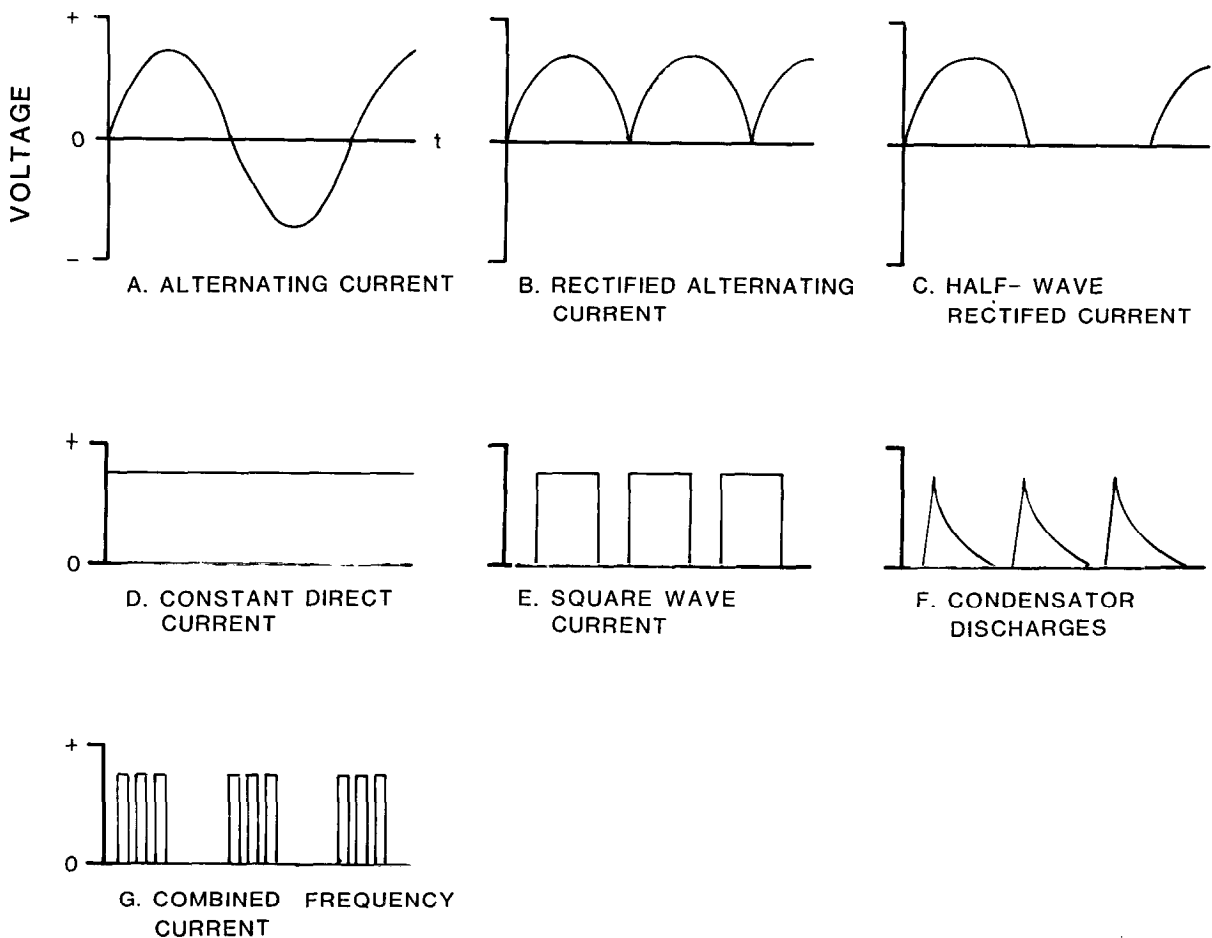


Fig. 2. Different shapes of current.

latter case the remaining pulse might be eliminated by the use of 3-phase current (op. cit.).

Direct and alternating current effect the physiology and behaviour of fishes in different ways (Halsband, 1967; Lamarque, 1967). At alternating current (Fig. 2A) the electrodes continuously alternate as anode and cathode, mostly at frequencies of 50 or 100 Hz (times per second). The fish is not attracted to either electrode. With direct current (Fig. 2B–G) the electrodes are permanently anode or cathode resp., but a quantitative change in voltage (regular or irregular) can be created. The fish is attracted to the anode and repelled by the cathode.

Either constant (Fig. 2D) or pulsed direct current can be used. The possibilities of variation in the pulse type are practically unlimited. The frequency can be varied regularly (generally

1–100 Hz) or by a combination of low frequency pulses compiled of a number of high frequency pulses (Fig. 2G). Moreover, the form of a single pulse can be varied from a rectified sine pulse over different forms of unregularly composed pulses (e.g. condenser pulses) to e.g. rectangular pulses (cfr. also Vibert, 1967; Sternin *et al.*, 1972).

Alternating current has a larger immobilization zone than direct current. As, however, direct current outside this zone has an attraction zone, the fishing efficiency of direct current might surpass that of alternating current (Fig. 4). Constant direct current has a lower physiological effect than any type of pulsed direct current as long as the total energy input per time unit into the water is equal (Vibert, 1967; Sternin *et al.*, 1972; Regis *et al.*, 1981; Hickley, 1985). The difference is more pronounced when immobilizing than when

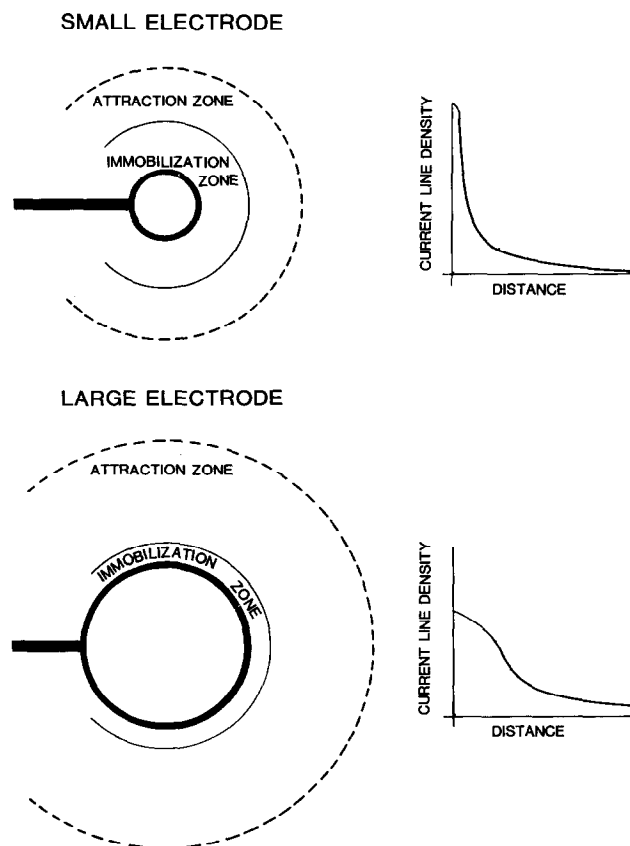


Fig. 3. The attraction and immobilisation zone (schematic picture) when using small and large electrodes (in the latter case with a higher current demand on the generator).

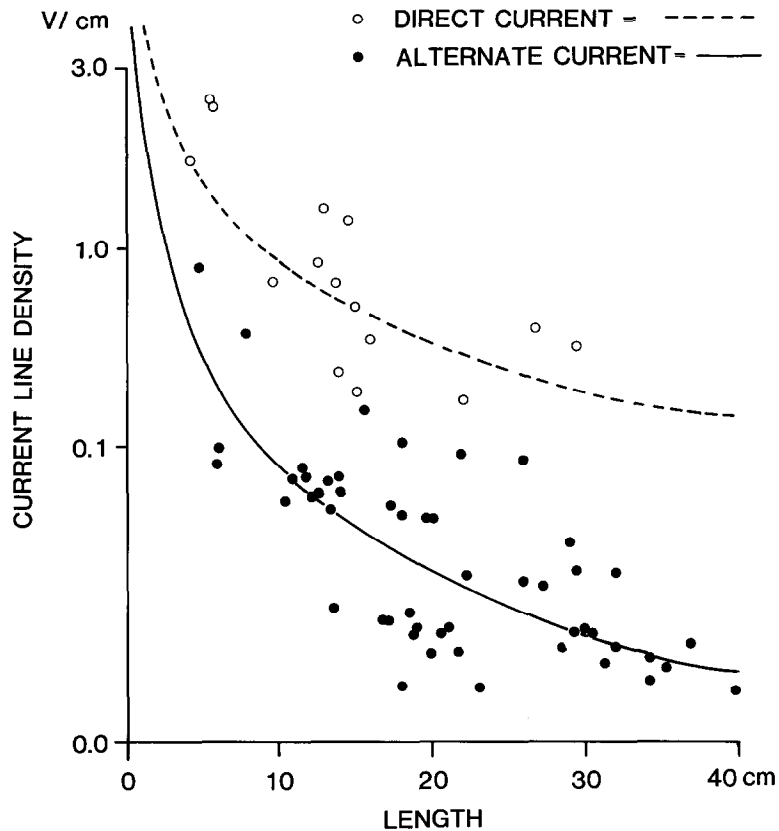


Fig. 4. Current line density needed for attraction of different fish species with direct and alternating current (data from Sternin *et al.*, 1972).

attracting the fish. By choosing the proper output effect, the zone of attraction can therefore be larger with constant than with pulsed direct current. The total fishing zone (including the immobilization zone) is, however, always larger with pulsed direct current. The former case might under certain circumstances be advantageous.

The physiological effect of pulsed direct current is positively correlated with both frequency (Sternin *et al.*, 1972; Hickley, 1985) and pulse length and is related to the duty cycle (frequency \times pulse length) according to a power function (Fig. 5). With a duty cycle exceeding 0.2 (1.0 = constant current) the effect of pulsed current surpasses that of constant current. The field strength needed for immobilisation is asymptotically reaching a minimum value at higher frequencies (for roach 0.2 v/cm at frequencies $>$ 50 Hz; Hickley, 1985).

When increasing the pulse length the attraction radius of the anode will asymptotically reach a value, which is dependent upon frequency, fish size and water conductivity. This value varies between 0.1 and 5 mS (Vibert, 1967; Sternin *et al.*, 1972). As, however, the effect needed increases linearly with the pulse length, an optimum pulse length (considering fishing efficiency and energy consumption) of 0.5–1.0 mS (10–40 Hz) is achieved.

The effect of varying the shape of the pulse is largely unknown. Vibert (1967) states, that condenser pulses (having a fast voltage increase and a slow decrease, cf. Fig. 2f) produce the largest effects. Sternin *et al.* (1972), however, were unable to find any empirical evidence for this statement.

The size and the material of the electrodes determine the current line density and the strength and corrosion resistance of the electrodes.

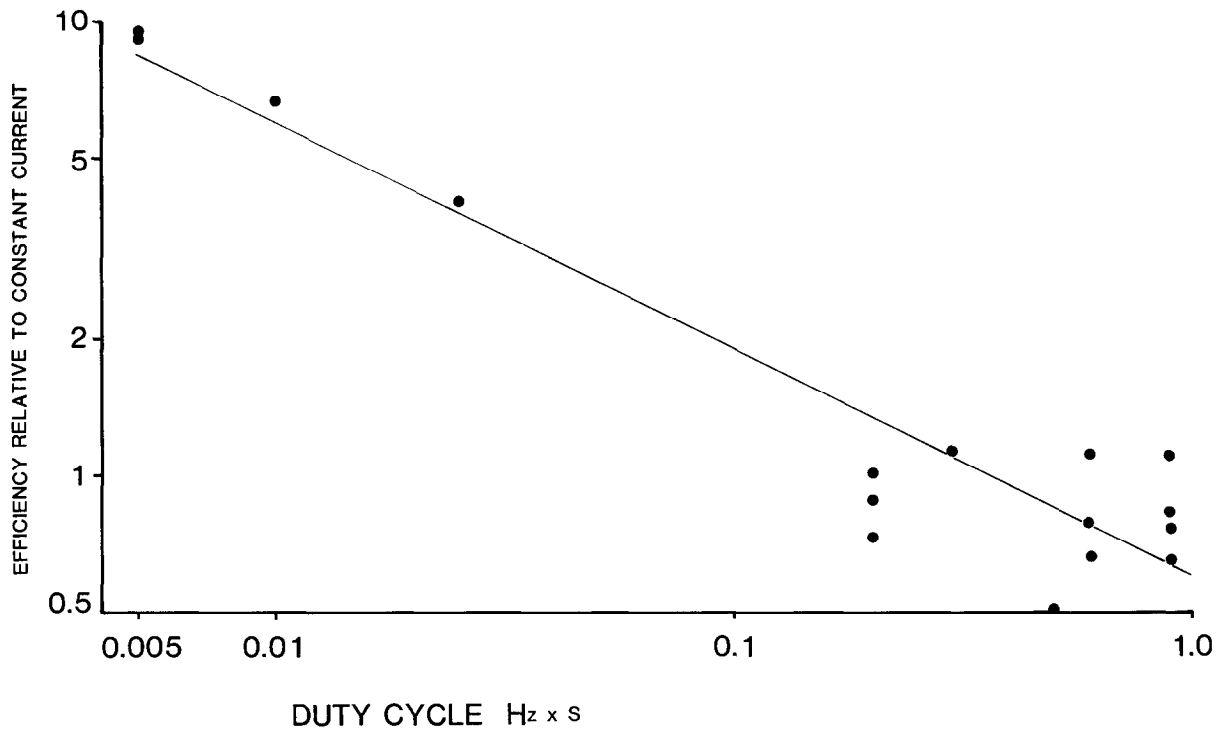


Fig. 5. Efficiency of direct versus pulsed current for immobilisation of fish (1 indicates equal efficiency) at different duty cycles (frequency \times pulse length).

Detailed studies of the relation between electrode size and fishing efficiency have been performed by Cuinat (1967) and Sternin *et al.* (1972). Large sized electrodes result in increased fishing efficiency and reduced fish mortality. The latter is an effect of the negative correlation between anode size and current line density (voltage gradient) in the water close to the electrode (Fig. 3). An increase of the anode diameter from 10 to 60 cm results in a three fold increase in the effective fishing area, while the maximum current line density is reduced from 40 to 17 V/cm (Cuinat, 1967). Alternatively the same fishing area would be achieved if the energy input was reduced from 5.9 to 2.7 kW (at 2700 μ S), while the anode diameter was increased.

The area of the cathode should be as large as possible and at least 3 times as large as the anode. In commercial fisheries the boat itself often serves as cathode. The upper size limit of the electrodes is mainly (especially for the anode) restricted by

manageability. In most cases an anode diameter of 40–60 cm is therefore the optimal solution. When a larger size is needed two anodes could be connected in parallel. The benefit of increasing cathode size is less pronounced at large sizes.

On theoretical basis Sternin *et al.* (1972) recommends spherical anodes, but Cuinat (1967) found only small efficiency differences between spherical and circular anodes when testing this empirically. Both anodes and cathodes could be shaped as rings or nets. Chicken wire is recommended as a cheap and light material for the cathode (Cuinat, 1967).

The corrosion of the material is mainly caused by electrolysis. When using direct current only the anode is affected. Corrosion increases with the energy output and is therefore mainly a problem at medium and high conductivities. The corrosion properties of different materials is expressed by the corrosion coefficient, which can be found in appropriate literature. Materials like chromium-

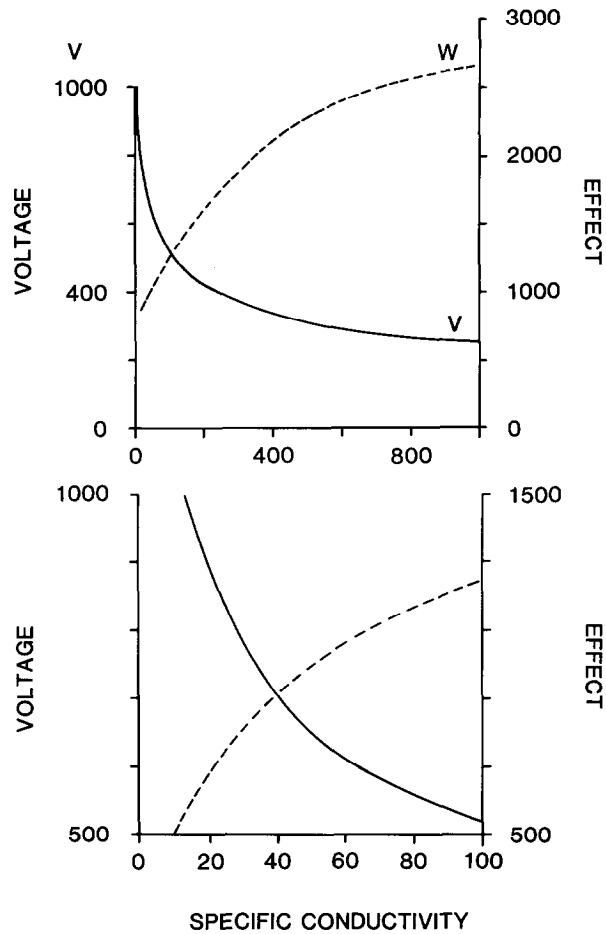


Fig. 6. Voltage and effect needed for electrofishing in waters with different specific conductivities varying between 0 and 1000 (top figure) and between 0 and 100 μs (bottom) (data for trout from Cuinat, 1967).

nickel steel and aluminium alloys combine strength and stability with low corrosion (Sternin *et al.*, 1972).

External factors

The possibility of using electricity for fishing is due to the fact that aquatic organisms, (both invertebrates and fishes) are immobilized (electronicosis), when the body voltage from nose to tail exceeds a certain value. With direct current, the fish will first show a fright response effect (negative electro taxis) resulting in efforts to escape the anode. Getting closer to the anode the fish will be attracted (positive electro taxis) show-

ing fast swimming movements towards the anode (forced swimming and galvano-taxis). Bringing the anode very close to the fish, it will be immobilized (galvanonarcosis).

The reaction distance depends on:

- 1) current line density
- 2) pulse type of electric current
- 3) fish size and species
- 4) the position of the fish in relation to the anode.

The current line density is in turn dependent upon water qualities (above all the specific conductivity) and the type of equipment used. Roughly speaking, when fishing with direct current a fish > 10 cm is repelled at 0.05–0.10 V/cm, attracted

at 0.1–0.3 V/cm and immobilized at 0.3–1.3 V/cm (Sternin *et al.*, 1972).

Biological factors

The physiological reactions of the fish towards alternating and direct current are different (see Halsband, 1967; Lamarque, 1967 for details). Using alternating current both the negative and positive electrotaxis are absent and the fish will show undirected swimming movements (oscillotaxis) or be immobilized depending on the distance from the anode. Alternating current has a stronger effect on the fish and the persistence of the reaction is much longer. This also implies that the risk for unwanted secondary effects (e.g. mortality) is larger (Sternin *et al.*, 1972). This is especially the case for small fish (< 10 cm).

Because of the stress imposed on the fish and the larger potential risk to the fisherman alternating current is less often used for electric fishing. In USA, however, alternating current with equipment often permanently installed in boats is frequently used for fishing (Heidinger *et al.*, 1983).

The length of the fish is of vital importance for the fishing efficiency (Vibert, 1967; Sternin *et al.*, 1972, Regis *et al.*, 1981), which increases exponentially with fish length, when alternate or constant direct current is used (Fig. 4, but see Chmielewski *et al.*, 1973). For large fish, however, this tendency may be counterbalanced by an increased flight radius or because of fast forced swimming in the attraction zone. Fishing with pulsed direct current did not give the same unambiguous result (cfr. Sternin *et al.*, 1972). This was probably due to the use of different equipment leading to differences in frequency, length and type of pulse. After correction for selectivity due to the length of the fish, the effect of pulsed direct current is proportional to the energy input per time unit (frequency \times pulse length).

In order to decrease the length selectivity, the current line density could be increased (Stewart, 1975). However, this would also increase the mortality of the fish.

Vibert (1967) and Sternin *et al.* (1972) state that

differences exist between fish species with respect to the reaction to the electric field. Differences in the internal specific conductivity between species is relatively large (a factor of 3) and might together with metabolic differences constitute the basis for such a difference (Sternin *et al.*, 1972). Studies of the voltage needed for attracting fish based on 20 species (Fig. 4) indicate, however, that factors like fish length and behaviour are more important. Regis *et al.* (1981) found no differences in attraction distance among the species tench (*Tinca tinca*), grayling (*Thymallus thymallus*), catfish (*Ictalurus melas*) and nase (*Chondrostoma nasus*).

In practice, differences in behaviour and habitat preference among fish species are more important for the fishing efficiency than physiological differences. Some pelagic and semipelagic species like the grayling *Thymallus thymallus*, tend to avoid the electric field, resulting in poor catchability (Ernst and Nielsen, 1981). The catchability of bottom dwelling organisms (eel *Anguilla spp.*, catfishes and sculpins *Cottus spp.*, lampreys *Petromyzon* and *Lampetra spp.*, and crayfishes), is strongly dependent on sediment conductivity and the possibility of locating immobilized animals. Compared to territorial salmonids bottom dwellers may therefore be underrepresented. Schooling species tend to be stunned in vast numbers, of which only a small fraction may be caught before the school has disappeared in vegetation or swept away by the water current.

Further considerations concerning the possibility of quantifying different fish species are discussed in the following section.

The initial orientation of the fish when influenced by an electric D.C. field is of major importance for the fishing efficiency. The fish will then instantaneously turn either from or towards the anode depending on the current line density. If moving when affected by the current, the resultant movement direction of the fish will be determined both by the original direction and speed of the fish and the position and density of the current lines. Instead of being attracted by the anode the fish might then either be forced away from the anode because of the centrifugal force or drawn towards it with such a speed, that it passes

through and out of the attraction and immobilization zones. This risk is positively correlated with the size of the fish and will therefore tend to reduce the positive size selectivity discussed above. It has been shown that fishes which originally are directed towards the anode are attracted more efficiently than fishes orientated in other directions (Sternin *et al.*, 1972). The attraction was especially fast with pulsating direct current.

With alternating current the orientation of the fish is of little importance as the attraction zone is lacking. The fish will be caught only when in the immobilization zone, within which the orientation of the fish is unimportant (Vibert, 1967; Sternin *et al.*, 1972).

When attracted the fish will follow the current lines. Fish close to the anode will then move directly towards it, while fish further away will move towards the anode in a curve like manner. Due to irregularities in the electric field close to phase boundaries (sediment/water or water/air) they might then swim into the sediment, often giving rise to bubble up-welling, or break the surface. The same reactions will occur for fish being repelled by the cathode and leaving it along the current lines.

Physical factors

Because of its effect on the voltage and the current line density the specific conductivity of the water is the most important physical-chemical factor. Using the same equipment, higher voltage will be achieved in waters with low opposed to high conductivity due to higher resistance in the former case. To compensate for the lower voltage obtained at high conductivities a more powerful generator is required, which will increase its size and weight. The need for increased power is somewhat reduced by the lower current line density needed for attraction at low conductivities (50% reduction in oligotrophic compared to marine waters; Lamarque, 1967).

The optimal effect with direct current is achieved at a voltage of approximately 300 V at

500 μS (Fig. 6). This value increases with decreasing conductivity to approximately 700 V at 25 μS . To achieve this voltage an effect of 2,5 kW will be needed in the first and 0.7 kW in the second case.

At very low conductivities ($< 20 \mu\text{S}$) the fishing efficiency is strongly reduced (Sternin *et al.*, 1972). The efficiency reduction reaches a minimum at approximately 5 μS (the value being dependent upon the inner conductivity of the fish).

The conductivity of the water varies with temperature. At 0 °C the conductivity of the water is reduced by 40% compared to 20 °C. The fishing efficiency will therefore increase with decreasing temperature (cfr. Bruscek, 1967). Moreover, for physiological reasons the fish will be less attracted by electricity at high temperatures (Vibert, 1967).

The existence of phase boundaries causes irregularities in the electric field. At the water/air boundary a compression of the current lines will occur, whereby the fishing efficiency is increased. At the water/sediment boundary the current lines will in most cases be attracted by the sediment, because of its generally higher conductivity (Sternin *et al.*, 1972). The fishing efficiency will therefore be reduced near the bottom. Electric fishing with ordinary equipment might be impossible and a short circuit could occur if the sediments are very rich in electrolytes, e.g. marine deposits or iron hydroxide.

In addition to the specific conductivity a number of other factors are important for electric fishing efficiency e.g. the transparency. The immobilisation radius is in most cases equal to or less than 0.5 m and adequate visibility within this distance corresponds to a secchi disc transparency of approximately 1 m (equal to 100 mg Pt/1). In humic and eutrophic waters the transparency rather than the attraction radius will therefore be the limiting factor. Under such circumstances there is less need to use stronger and heavier power units. Limited transparency will also cause a more pronounced size selectivity as the probability of seeing the fish within the immobilisation zone will be positively related with its size.

The lower catchability of bottom dwelling animals and in vegetated areas has been mentioned. The animals will often be immobilized out of sight of the fisherman. It may then be advantageous to use constant rather than pulsed direct current. This will shorten the attraction radius, but is partly compensated for by a reduction in the immobilization radius. Thus the possibility of getting the animals out of their cover before they are immobilized will increase. When catching (or affecting) large decapodes like crayfishes it is also advantageous to use constant direct current as the risk of the animals losing their claws will be reduced. An interesting combination unit for catching bottom dwelling animals have been constructed by Phillips and Scolaro (1980). They used constant direct current to make the animals leave cover, after which alternating current (0.1 V/cm) was used to immobilize the attracted animals.

Population estimation

Introduction

This section and the next concern estimating population size and population changes from electrofishing data. In this section we review some widely used – and useful – methods of assessing the number of fish in a closed site of a stream or the littoral zone of a lake, and in the next this theme is continued with the next question – how to select these sites and how to make more general statements about stocks.

Unfortunately the methods of population estimation are not easily accessible for people not trained in statistics. We have therefore tried to make the presentation as clear as possible. The calculations require only a pocket calculator with preprogrammed functions for mean and standard deviation, and the examples provided are intended to facilitate the use of the methods.

Before these are presented, however, it might be useful to recall some basic statistical concepts.

Statistical and systematic errors

There are seldom opportunities to obtain exact measurements of the size or density of fish populations. Rather, the true population size y is estimated as \hat{y} , more or less close to the true but generally unknown y .

As an estimate with unknown error is quite useless, several ways of expressing and estimating these errors have been developed. The types of error that may arise can be illustrated by firing a rifle at a target (Fig. 7). If the shot group is tight but its center at a distance from the bullseye, the *statistical error* or *sampling error* is small, but the *systematic error* large and represented by the distance between the center of the shot group and the bullseye. This distance is the *bias*. If the sampling error of an estimate is small, the *precision* is good, and if the bias is small, the *accuracy* is good.

A biased method of estimation will, on the average, yield either over- or underestimation (positive or negative bias). There are usually no easy ways to assess the bias of estimates of natural populations. Occasionally it is possible to apply a specific method to populations of known size, e.g. marked members, and thus get an idea of the bias. Further, if two methods are applied to the same population of unknown size, at least one of them is biased if the estimates, on the average, differ. Finally, a critical look at the assumptions on which the method is based will often reveal at least the direction of the bias.

The sampling error has the effect that the estimate \hat{y} would fluctuate around a mean $E(\hat{y})$ if, hypothetically, the estimation were repeated many times under identical conditions. This fluctuation can be measured as the *sampling variance* $V(\hat{y})$ of \hat{y} , which is the average value of the squared deviations $E(\hat{y} - \hat{y})^2$. The square root of $V(\hat{y})$ is called the *Standard Error* of \hat{y} , or $SE(\hat{y})$. This can be viewed as a direct measure of this (hypothetical) fluctuation (Fig. 7).

Another useful measure of the sampling error is the *coefficient of variation* $C = SE(\hat{y})/\hat{y}$, indicating the relative sampling error.

In addition it may sometimes be possible to estimate the sampling error (or its effects) as a

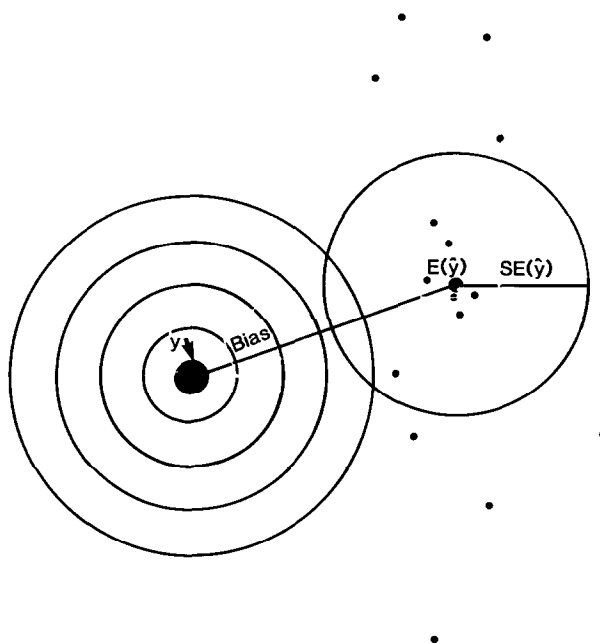


Fig. 7. Analogy between shooting result and estimation. The center of the target represents the true population size y , and the bias the distance between the center of the target and the center $E(\hat{y})$ of the shot group. The mean distance between the shots (dots) and the center of the shot group represents the sampling error $SE(\hat{y})$.

confidence interval about the estimate \hat{y} . A 95% confidence interval has the meaning that the true (but unknown) y is included in this interval in 95 cases out of 100 if, hypothetically, the estimation were repeated many times. The calculation of the confidence interval is often based on the Standard Error.

Finally a word about the measurement of the *spatial variation* of a population. Anyone familiar with fish sampling has observed that the density of fish usually varies from site to site. Suppose that the total area in which the population lives is divided into a number of smaller units. The *mean density* per unit, \bar{y} , is then the total population size divided by the number of units. The (spatial) *variance* $V(y)$ of y is the mean value of the squared deviations $(y - \bar{y})$ over all units, and the *Standard Deviation* $SD(y)$ of y the square root of $V(y)$. $SD(y)$ is a measurement of how much the population size in the units differ, on the average, from the population mean \bar{y} . Observe the similarities and differences of $SE(\hat{y})$ and $SD(y)$; the former is a measurement of the *precision* of an estimate \hat{y} ,

and the latter is a measurement of the *spatial variation* of the population. $SD(y)$ and \bar{y} are most easily calculated using a calculator with pre-programmed functions.

Precision requirements

In all studies the attempt is, of course, to obtain as good a precision as possible. The problem is that increased precision usually has to be paid for in time, work and money. In addition, the precision requirement is intimately linked to the type of question that is to be answered.

As an example, say we are interested in comparing the fish densities in two streams. Estimation yields \hat{y}_1 and \hat{y}_2 , respectively. If both estimates have poor precision, we may not be able to tell if there is any real difference between the true densities, unless the estimated difference is very large. For some purposes, thus, a poor precision may make the study quite worthless. On the other hand, if we are interested merely in dis-

covering drastic differences, the same precision may be sufficient. In the planning of surveys it is therefore important to state the precision requirement as clearly as possible and try to design the work for the precision level chosen. One way to classify the precision is the following¹. C is the coefficient of variation as defined above.

Class 1. With this precision, a population change of a factor of ~ 1.2 in time or space (e.g. 83–100–120) is discovered in ~ 95 cases of 100. This corresponds, roughly, to $C = 0.05$ for independent estimates. This precision may be required if the estimate is to be divided or multiplied with other estimates, or when good precision is called for.

Class 2. With this precision, a population change of a factor ~ 1.5 in time or space (e.g. 67–100–150) is discovered in ~ 95 cases out of 100. This corresponds, roughly, to $C = 0.10$ for independent estimates. This level is suitable in many cases, e.g. when classifying fish density in, say, 4–5 quality classes from ‘very bad’ to ‘very good’.

Class 3. With this precision, a population change of a factor ~ 2 in time or space (e.g. 50–100–200) is discovered in ~ 95 cases out of 100, corresponding to $C = 0.20$ for independent estimates. This precision may be sufficient when classifying fish densities as ‘bad’, ‘intermediate’ and ‘good’, or when the object is to give alarm if a population is reduced to less than half of its original size.

These precision classes will be referred to in the following text, especially in the section concerning the sampling design.

Mark-recapture methods

We now turn to one of the methods of assessing the population size in a closed area, the mark-recapture methods. These are based on the recap-

ture of a known number of marked or tagged individuals. In the more sophisticated versions, requiring individual tagging or at least batch marking and repeated marking-recapture (see Seber, 1973; pp. 59–292), it might be possible to estimate migration and mortality in addition to population size. As electrofishing usually is used to assess the number of small fish (for which individual tagging is often difficult) in closed sections of streams, the simplest mark-recapture estimator called the Petersen method may be used. If m individuals are caught, marked (e.g. by fin clipping) and released, and if c individuals are caught on a second occasion, of which r are found to be marked, an estimate \hat{y} of the populations size y is

$$\hat{y} = mc/r \quad (1)$$

An estimate of the sampling variance $V(\hat{y})$ of \hat{y} is

$$\hat{V}(\hat{y}) = \frac{\hat{y}^2(\hat{y} - m)(\hat{y} - c)}{mc(\hat{y} - 1)} \quad (2)$$

and of the Standard Error $SE(\hat{y})$

$$SE(\hat{y}) = \sqrt{\hat{V}(\hat{y})} \quad (2')$$

Approximate 95% confidence limits are

$$\hat{y} \pm 2 SE(\hat{y}) \quad (3)$$

The catch probability, or catchability, p , in the second catch is estimated as

$$\hat{p} = r/m \quad (4)$$

Example 1. $m = 66$ trout yearlings were marked and released into a closed section of a stream. Later $c = 54$ trout were captured, of which $r = 32$ were marked. Then

$$\hat{y} = 111.4$$

$$\hat{p} = 0.485$$

$$SE(\hat{y}) = 9.07$$

$$95\% \text{ confidence limits } 93.3 - 129.5$$

$$C = SE(\hat{y})/\hat{y} = 0.081 \text{ or } 8.1\%$$

¹ Based on normality of the estimates and not to small samples.

The population estimate (eq. (1)) is negatively biased even if all assumptions are met; the bias, however, is negligible if mc/y is larger than about 4 (Youngs and Robson, 1978). In practice, therefore, the bias introduced by deviations from basic assumptions are probably of greater importance and is discussed below.

As the catchability of electrofishing in streams is often in the magnitude of 0.50, the confidence interval (3) is approximately valid if c is larger than about 30 (or the population size larger than about 60). If the catchability is lower, larger populations are required for valid confidence limits (Cochran, 1963; p. 57).

Robson and Regier (1964) provided graphs for determining sample size when using the Petersen estimator. These are highly useful when planning the study of large, mobile populations, e.g. fish populations in lakes. When applying the Petersen method to closed sections in streams or in the littoral zone of lakes using electrofishing both for capture and recapture, the situation is somewhat simpler. Assuming that the whole area is suitable for electrofishing and that both fishings are equally efficient, the coefficient of variation $C = SE(\hat{y})/\hat{y}$ is, from (2),

$$C = (1 - p)/(p\sqrt{\hat{y}}) \quad (5)$$

From this expression we have calculated the expected C values for some various population sizes y and catchabilities p . These are given in Table 1 and may be compared with the precision classes suggested above. If p is 0.6 or larger the precision obtained usually corresponds to Class 1. Note, however, the combined effect of small populations and low catchability.

Table 1. Coefficient of variation $C\%$ for the Petersen estimator for various values of population size y and catchability p . The assumption is that both captures have the same p . Relative precision of the Petersen estimator.

	$y = 50$	$y = 100$	$y = 200$	$y = 400$
$p = 0.4$	21	15	11	7.5
$p = 0.6$	9.4	6.7	4.7	3.3
$p = 0.8$	3.5	2.5	1.8	1.3

Of the assumptions on which the Peterson estimator is based (see Seber, 1973; p. 59), the following are probably the most critical ones in connection with electrofishing:

1. Equal catchability of all individuals. Electro-fishing is selective: large individuals have on the average and for many populations a larger catchability than small ones, and individuals in certain biotopes (territories) may be harder to catch than an average individual. The result is a *general underestimation* of the population size. The effect of size selection can be ruled out if separate estimation for each size class is carried out (which, however, may result in small populations and hence reduced precision). Unequal catchability depending on biotope heterogeneity within the area will remain.
2. Catchability is the same for marked and non-marked members. Though electrofishing is one of the most harmless sampling methods if used properly, the experience is that an electric shock will reduce the catchability for some time. This time may vary widely depending on species, size, temperature, electric field strength, skill of the fisherman etc. Peterson and Cederholm (1984), working with juvenile coho salmon, found that catchability returned to acceptable levels after a 1 hour time lapse, but that it did not quite equalize even after 24 hours. If the catchability is reduced as a result of handling, r will be below expectation and the population size y therefore overestimated. In practice, deviations from assumptions (1) and (2) will therefore tend to offset each other.
3. A random sample is obtained in the second fishing. For stationary fish spread over an area possible to cover with electrofishing, this assumption is probably well met. For schooling species, where there is a possibility of missing the school in one of the fishings, the estimates may become quite misleading. The Petersen method should therefore be applied with care to schooling species in large bodies of water.

A practical limitation of mark-recapture methods is that the fish individuals often are

too small for individual tagging, and thus that one may encounter problems separating marked members from those that were marked on previous occasions. If this is not a problem, clipping of the adiposal fin may be the best marking method. For short term studies, other fins may be used, or various branding methods.

The removal method

The second type of method used to estimate population size in a small, closed area is the removal method. This is the method most widely used to estimate the population size of fish in streams or the littoral zone of lakes when using electrofishing and can be used if the capture is efficient enough to reduce the population size substantially.

To apply the removal method, the following assumptions should be fulfilled (Seber, 1973; p. 312):

- (1) The population is closed
- (2) Equal catchability for all individuals
- (3) Equal catchability among the removals

The general case of k removals

To get estimates of population size from successive removals, one method is to use the maximum likelihood estimator developed by Moran (1951) and Zippin (1956). As there is no general explicit solution, Zippin (1956, 1958) provided graphs by which the population size and the catchability can be estimated in the case of 3, 4, 5 and 7 removals. If k = the number of removals, c_1, c_2, \dots, c_k = the catch in each consecutive removal, $T = (c_1 + c_2 + \dots + c_k)$ = total catch, p = catchability, and $q = 1 - p$, a more flexible method is to let a computer estimate q by iterative solution of the expression

$$\frac{\hat{q}}{\hat{p}} - \frac{k\hat{q}^k}{1 - \hat{q}^k} = \frac{\sum_{i=1}^k (i-1)c_i}{T} \quad (6)$$

In (6), the sum in the last term is $c_2 + 2c_3$ for $k = 3$, and $c_2 + 2c_3 + 3c_4$ for $k = 4$ and so on. If (6) is used for iterative solution, a first guess of $\hat{p} = c_1/T$ can be used. The population size y is estimated by using the \hat{q} value obtained in the expression

$$\hat{y} = \frac{T}{(1 - \hat{q}^k)} \quad (7)$$

The sampling variances of \hat{y} and \hat{p} are

$$\hat{V}(\hat{y}) = \frac{\hat{y}(1 - \hat{q}^k)\hat{q}^k}{(1 - \hat{q}^k)^2 - (\hat{p}k)^2\hat{q}^{k-1}} \quad (8)$$

and

$$\hat{V}(\hat{p}) = \frac{(\hat{q}\hat{p})^2(1 - \hat{q}^k)}{\hat{y}[\hat{q}(1 - \hat{q}^k)^2 - (k\hat{p})^2\hat{q}^k]} \quad (9)$$

The Standard Errors are the square roots of (8) and (9). For confidence limits, see (3).

Although (6) and (7) are readily programmed into a computer, it is sometimes convenient, e.g. in the field, to use simpler methods. One such, yielding practically the same result as the method above, and which to our knowledge has not been previously used, is the following. An estimator of q is⁽¹⁾

$$\hat{q} = \frac{T - c_1}{T - c_k} \quad (10)$$

with the notation above. To obtain population size, (7) is used.

Another simple method is Hayne's (1949) graphical regression method. The relations (10) and (7), however, are as simple to use, less subjective and therefore recommended in favour of Hayne's method.

The case of 3 removals

Junge and Libosvsky (1965) found explicit solutions of \hat{y} and \hat{p} in the case of $k = 3$. As this case is of special interest, the solutions are given

⁽¹⁾ Derived in appendix 1.

below. First, compute $A = 2c_1 + c_2$ and T . y is then estimated as

$$\hat{y} = \frac{6A^2 - 3AT - T^2 + T\sqrt{T^2 + 6AT - 3A^2}}{18(A - T)} \quad (11)$$

and p as

$$\hat{p} = \frac{3A - T - \sqrt{T^2 + 6AT - 3A^2}}{2A} \quad (12)$$

The Standard Errors of these are given by (8) and (9).

Example 2. $c_1 = 244$, $c_2 = 86$ and $c_3 = 43$. Then,
 $A = 574$
 $T = 373$
 $\hat{y} = 398.4$
 $S\hat{E}(\hat{y}) = 8.17$
 $\hat{p} = 0.600$

If, instead, (10) and (7) are used,

$$\hat{p} = 0.609$$

$$\hat{y} = 396.7$$

The case of 2 removals

In the case of 2 removals (e.g. Seber and LeCren, 1967) the estimators are

$$\hat{y} = c_1^2 / (c_1 - c_2) \quad (13)$$

$$\hat{V}(\hat{y}) = \frac{c_1^2 c_2^2 (c_1 + c_2)}{(c_1 - c_2)^4} \quad (14)$$

$$\hat{p} = 1 - c_2 / c_1 \quad (15)$$

$$\hat{V}(\hat{p}) = c_2(c_1 + c_2) / c_1^3 \quad (16)$$

The Standard Errors of \hat{y} and \hat{p} are the square roots of (14) and (16), and confidence limits as in (3). (13) may be corrected for bias:

$$y^* = \hat{y} - \frac{\hat{q}(1 - \hat{q})}{\hat{p}^3} \quad (13')$$

where \hat{y} is calculated from (13).

Using an approximately known catchability

Under similar conditions a skilled electrofisher may have an approximately constant efficiency or catchability. If this p is estimated by some of the methods proposed above and can be assumed constant, it can be used either to get population estimates where only one removal has been carried out, or to increase the precision in the case of two or more removals. This method is especially valuable if the population size in a specific area is very low (e.g. older fish), as the methods above may fail or at least give poor precision in this case. The rationale is that q is estimated from a large population (e.g. the pooled result from several sections) where at least 2 or, better, 3 removals have been carried out. This \hat{q} , which thus has a good precision, is used in (7) to calculate the size of the 'small' population or the population in which few removals have been performed. As an example (*example 3*), 3 removals were carried out in each of 17 sections in a trout stream, yielding, totally, 1002, 213 and 68 trout of age 1+. From eq. (12) \hat{p} is 0.761 and $\hat{q} = 1 - 0.761 = 0.239$. In section No. 18 the fishing had to be interrupted after 1 fishing, yielding 65 trout of this age class. Then from (7), $\hat{y} = 85.4$ in section No. 18. *Example 4.* In section No. 19, the catch from 3 removals was 2, 2 and 0. The population is too small to apply eq. (11) (see below), so the p estimate from example 3 is used. Using (7), a population size $\hat{y} = 4.06$ is obtained for section No. 19.

The precision in this case is partly determined by the precision of the p estimate applied. Bohlin (1981) showed that the sampling variance, provided that the population is not too small, is approximately

$$\hat{V}(\hat{y}) = \frac{\hat{y}\hat{q}^k}{1 - \hat{q}^k} + \hat{V}(\hat{p}) \left(\frac{\hat{y}k\hat{q}^{k-1}}{1 - \hat{q}^k} \right)^2 \quad (17)$$

Using the data from *example 3*, the following result is obtained:

$$\hat{y} = 85.4$$

$$\hat{p} = 0.761 \text{ (eq. 12), } \hat{q} = 1 - 0.761 = 0.239$$

$$\hat{V}(\hat{p}) = 0.000155 \text{ (eq. 9)}$$

$$k = 1$$

$$\hat{V}(\hat{y}) = 28.77 \text{ (eq. 17), } S\hat{E}(\hat{y}) = 5.36$$

Table 2. Coefficient of variation C % for the removal method for various values of population size y , catchability p and number of removals k . *Relative precision of the removal method.*

		$y = 50$	$y = 100$	$y = 200$	$y = 400$
$p = 0.4$	$k = 2$	42	30	21	15
	$k = 3$	19	13	9	7
	$k = 4$	10	7	5	4
$p = 0.6$	$k = 2$	14	10	7	5
	$k = 3$	6	4	3	2
	$k = 4$	3	2	1.5	1
$p = 0.8$	$k = 2$	4	3	2	1.5
	$k = 3$	1.4	1	0.7	0.5
	$k = 4$	0.6	0.4	0.3	0.2

Precision

To illustrate how the precision, expressed as the coefficient of variation, depends on p , k and y , we have prepared Table 2. From this it is evident that the precision is particularly dependent on k and p , viz. the sampling fraction. For many salmonid populations, p is often in the magnitude of 0.5 or more. If 3 removals are carried out in this case, the precision corresponds roughly to Class 1. Note the disastrous effect of the combination small populations, low catchability and few removals. It can also be noted that there is generally a substantial gain in precision from 2 to 3 removals. A third removal may take little extra time to carry out, at least in high density biotopes. It may therefore be worthwhile to make 3 removals in favour of 2. If p is lower than 0.5, more removals may be required.

There is an additional reason to apply 3 rather than 2 removals. For the 2-catch method, the standard error estimate seems to be of doubtful value for populations smaller than about 200, whereas the 3-catch method may tolerate populations down to about 50 (Seber, 1973; Bohlin, 1982).

If the population is small, there are thus two problems. The first is that the relative precision, C , will be poor, and the second that both the population size and its variance are hard to estimate. This is especially true for $k = 2$, in which case the method may fail totally. These problems,

however, seem easy to overcome by using an approximately known p value, estimated from a larger population as in examples 3 and 4. If so, the precision also from very small populations may be quite good, provided that the small population is fished at least 3 times. The problem of estimating this precision remains. As will be shown below, however, this may not be a major drawback. On the assumption that the catchability is reasonably constant, we recommend the use of an approximately known catchability if the population is smaller than about 50, or if the first catch yields less than about 25, or if fewer than 3 removals are carried out.

Accuracy

The accuracy of the removal method depends on how well the basic assumptions are valid for real populations. One of the major sources of inaccuracy is probably a catchability which varies among individuals in the population. As the catches in this case are dominated by individuals with a catchability above the population average, the result is an overestimation of p and hence an underestimation of population size. To illustrate this, consider a population in which one half is living in a biotope where the individuals are impossible to catch, and that the other half is living in a biotope in which the catchability is 0.5. The removal method in this extreme population will yield an estimated catchability of about 0.5, although the real catchability was 0.25 in the first catch, 0.125 in the second etc. Further, the estimate of the population size would be half of the real number. The effect of a catchability forming a continuous distribution rather than discrete values as in the example above is similar, but the degree of underestimation of population size is heavily dependent on the shape of this distribution. The most serious bias is expected when a large fraction of the population has a catchability considerably lower than the population average. It has also been shown (Seber and Whale, 1970; Bohlin and Sundström, 1977), that the underestimation caused by an individually varying catchability increases with decreasing mean catchability. When evaluating estimates based on

the removal method, the following should be considered:

- (1) A large *estimated* catchability is never a proof that the real catchability is large and that the amount of underestimation is small.
- (2) A low estimated catchability indicates that the underestimation may be large and the precision poor.
- (3) In order to evaluate the magnitude of the underestimation, the method should be checked against a population of known size under realistic conditions.

Implicit in the trapping theory on which the removal estimator is based is the assumption that the catchability of one individual is independent on the catchability of other individuals. This assumption may be seriously violated for schooling species for which individual schools rather than individual fishes may follow the theory, resulting in a breakdown of the estimator.

As there are few studies in which estimates have been checked against known populations, the accuracy of the removal method for various species is largely unknown. From the behaviour and habitat, however, it might be possible to make some inferences of the catchability distribution and hence state some general guidelines:

1. For schooling species, the catches may not be binomially distributed as assumed, and the estimates may be totally misleading.
2. For species which are stunned rather than attracted by the voltage gradient, a population fraction may not be detected. This would lead to increased underestimation. Some cyprinids, e.g. the minnow, may belong to both categories (1) and (2).
3. Species living in dense vegetation or in the bottom substrate will be underestimated to a larger extent than species that live in open water, especially if it is combined with (2).
4. Some species living in open water will tend to avoid the voltage gradient, e.g. the grayling. The catchability is therefore low and estimates may be of doubtful value.
5. For territorial salmonids in shallow, clearwater streams with little vegetation, the catchability

seems to approach the assumptions on which the removal method is based to a larger extent than the foregoing categories. Even so, however, Bohlin and Sundström (1977) demonstrated unequal catchability in populations of juvenile trout and also the effect of this – a general underestimation of about 15% for yearling trout.

Generally, thus, the removal method will probably yield an underestimation of population size. The magnitude of the bias is affected both by species specific behaviour and by habitat conditions affecting the possibility of locating or catching fish in the voltage gradient.

The main goal of electrofishing studies is often to monitor population changes rather than to obtain absolute figures of fish density. If the bias is proportional to population density – which does not seem unlikely – the relative change can be obtained without serious bias. In absolute terms, however, a certain bias will remain.

Comparisons between the removal method and the Petersen estimator

For p values of ordinary magnitudes the 3-catch method and the Petersen estimator have similar precision. On the assumption that fishing/mark-ing does not affect the fish, both methods are about equally sensitive to deviations from the assumption of equal catchability (Bohlin and Sundström, 1977). As electric shocking may lower the subsequent catchability, this will lead to a further underestimation of the removal method, but a reduced underestimation if the Petersen method is used. The Petersen method will therefore yield larger and probably more accurate estimates than the removal method (Cross and Stott, 1975; Heggberget and Hesthagen, 1979; Petersen and Cederholm, 1984) and might be the best choice if accuracy is important. Normally, the removal method is still valid, provided a time lapse, possibly in the magnitude of at least half an hour, between the removals.

Sampling design and stock assessment in streams

Introduction

So far we have been dealing with the question of how to estimate the fish population in a closed area in a stream or in the litoral zone of a lake. We have also found methods well suited for this purpose, at least for some species.

It is evident, however, that even if an exact estimate were obtained from, say, pool 'A', this figure is in most cases quite uninteresting. It becomes useful first when we from this figure can say something about the fish population in the stream. It is also evident that if the population is heavily varying from site to site, then we have to study several such sites to make conclusions about the whole population. So first we have to define the population about which statements are to be made, and then decide the size and number of sites to be investigated, and finally find out how to select these sites and how to calculate population parameters from the result.

Too little attention has been paid to these questions (Bohlin, 1981; Hankin, 1984), though great savings may be the result if the field work is well organized (or great losses if it is not).

The target area

The first crucial point in the planning of a sampling programme is to define the target area (sampling universe). The target area is the total stream area (or in some cases stream length) that one wishes to make statements about and in which it is possible to carry out quantitative electrofishing. In most applications the aim is to make statements of the population, or to compare e.g. 'disturbed biotopes' with 'natural biotopes'. In the first case the target area is the total fish-producing area in a specific stream (minus the fish-producing areas in which electrofishing is impossible). In the latter case there are two target areas, of which the first one is the total area of 'disturbed biotopes' in the stream and the second the total area of 'natural biotopes'. In large streams it is important

to note that statements about the fish population are limited to the population fraction in areas (biotopes) where electrofishing is possible, so that the target area may comprise only a minor fraction of the total stream.

Even small streams may be too large for a total survey, and one has to select the sampling areas and determine the number and size of these. On the other hand, if the target area is very small a total survey may be practical, and no subsampling is needed.

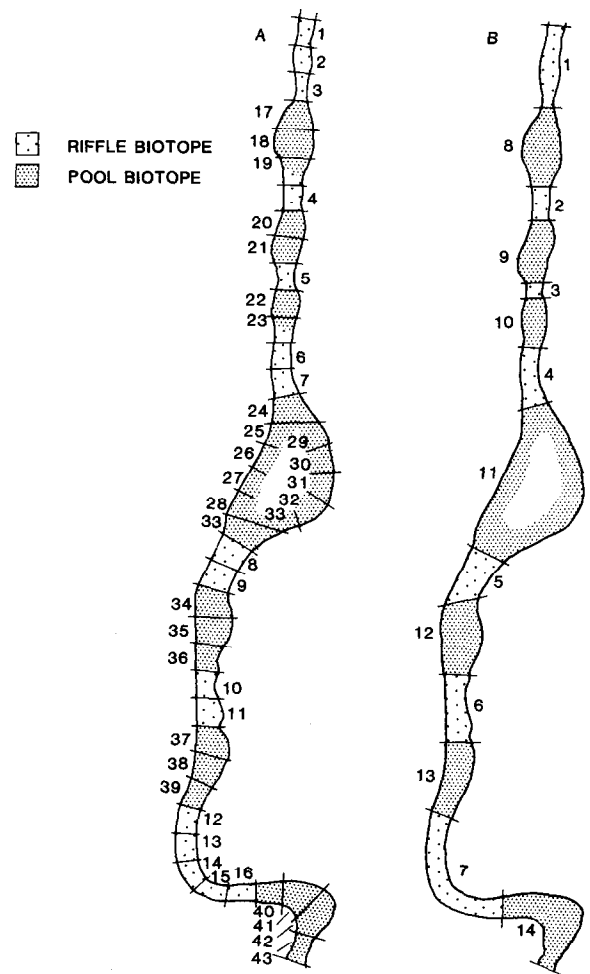


Fig. 8. A stream divided into N sampling areas using (a) units of equal length, (b) units of a size varying according to biotope variation. A sample of units may be obtained using simple random sampling in (a) and (b) or by proportional probability sampling (b). The target area is the whole stream except for the deepest part of the pool in the middle of the stream. See also Fig. 9.

The sampling area

If the target area is too large for a total survey, the next step is to define the sampling area, which in this context is electrofishing sections within the target area. There are two main ways of defining these: of equal size (usually length) or of unequal size. In Fig. 8a, the target area is divided into 43 sampling areas (units) of equal length. In Fig. 8b, the target area is divided into 14 sampling areas (units) of a size which is allowed to vary according to natural variations in biotope. The following considerations may give some guidance in the choice of approach. N is the total number of units within the target area.

Size of the sampling area

To obtain sampling areas of suitable size, it is generally better to divide the target area into many small sections than few very large ones. The reason is that the methods of stock assessment proposed below may require an N value not too small. There may, however, be problems if the units are very small. Regardless whether blocking nets are used or not, the displacement of fish from the area due to disturbance is likely to increase with a decreased section area, especially in large streams where edge effects will be more pronounced. Further, the large sample theory on which the Petersen method and the removal method are based may not apply if the population in a section is small. The minimum section size is therefore dependent both on the type of stream and the population density.

Equal or unequal size of sampling areas

Hankin (1984) recommended a design based on sampling areas with a size varying according to the biotope variations (Fig. 8b). This design is especially suitable if the biotope units (pools, riffles etc.) are of a practical size (see above).

In a large stream they may be far too large. Sometimes, especially in small streams, sections of equal length are used, mainly because the computation of total stock in this case only requires knowledge of total stream length. There are reasons to be flexible; in a stream with long uni-

form riffles, occasionally interrupted by pools of varying area, a suitable design may be to let the 'pool sections' size vary with the actual area of the pools and to choose 'riffle sections' of approximately equal length.

The number of sampling areas

We have now defined the sampling universe, which in this case is the target area divided into a number N of sampling areas. The next question is how many of these should be sampled and how to select them.

The number of sampling sections required depends on (1) the precision level required (e.g. Class 1, 2 or 3), (2) the variation of the fish population between the units, and (3) the size of the target area, expressed as N (total number of units). For a specific study, the precision level is chosen and N known, so to get an idea of the sample size needed we must have some additional information on the spatial variation of the population.

For salmonids in streams it appears that the spatial variation, expressed as the population coefficient of variation $C_p = \text{Standard Deviation } s / \text{mean } \hat{y}$, often is of similar magnitude despite large differences between populations and streams. In Table 3 we have compiled some data, ranging from large Northern streams (Alta) to small southern streams (Norum). It is therefore surprising that C_p seems to be relatively constant (mean about 0.8, approximate range 0.5–1.0). This can be utilized in the following way.

First, choose an appropriate level of precision, expressed as C (for example 0.1 if Class 2 is chosen). Then, using either your own data or consulting Table 3, find a preliminary C_p value. A crude magnitude of the number n of sections that has to be sampled to reach the precision level chosen is then

$$n = C_p^2 N / (C^2 N + C_p^2) \quad (18)$$

If Class 2 is chosen ($C = 0.1$) and $C_p = 0.8$ is taken from Table 3, and if the stream in Fig. 8a is

Table 3. The population coefficient of variation $C_p = SD/\bar{y}$ for salmon and trout in streams of varying type. n = sample size.

¹ Section area varying, mean 100 m². C_p calculated for density. Data from S. J. Saltveit.

² Section area varying mean about 200 m². C_p calculated for population size. Data from T. G. Heggberget.

³ Section area varying between 77 and 444 m². C_p calculated for density. Data from E. Jutila.

⁴ Section length 100 m, area varying. C_p calculated per section. Data from T. Bohlin.

Spatial variation of some salmonid populations in streams.

Stream	Mean width (m)	Time	Age class	Atlantic salmon		Brown trout	
				n	C_p %	n	C_p %
Laerdal ¹	~ 30	1980/9	0	13	113	14	83
			1	15	110	13	116
		1980/10	0	13	63	12	58
			1	13	77	13	93
Alta ²	~ 70	1981/9	> 0	15	82		
		1982/8	> 0	16	85		
		1983/9	> 0	16	72		
Simojoki ³	~ 40	1983	> 0	14	101		
Jörlanda ⁴	3.6	1982/9	0			20	73
			1			20	45
		1983/9	0			20	65
			1			20	29
Norum ⁴	2.4	1982/9	0			20	96
			1			20	60
		1983/9	0			20	77
			1			20	88

the target area ($N = 43$), it would take about $n = 26$ sampling areas to obtain this precision. If Class 3 is sufficient, n is reduced to about 12.

So, although the sample size calculated from eq. (18) is just a crude and preliminary magnitude, it is clear that stream surveys even of moderate precision levels will usually require a large number of sampling areas. Therefore, choosing a sample size n matching the aim of the study is one of the most crucial steps in the planning procedure. We have therefore used eq. (18) to construct Tab. 4, illustrating how the sample size required depends on C , C_p and N . From this table it is evident that Class 1 might be hard to obtain unless the target area is very small.

It is to be stressed that the sample size calculated from eq. (18) should not be taken too literally. We have ignored possible effects of stratification (see below) etc. It might therefore be valuable to make checks of the precision obtained during the field work.

Stratification

We now have a rough idea of the sample size required. The next problem is how the areas should be distributed in the stream.

We often know enough of the relation between the type of biotope and the fish abundance to state

Table 4. Sample size n required to reach a given precision class for various combinations of N = total number of units and C_p = population coefficients of variation = SD/\bar{y} . C is the precision requirement, expressed as the coefficient of variation of the estimate. *Sample size and precision classes, independent data.*

		$N = 25$	$N = 50$	$N = 100$	$N = \infty$
Class 1 ($C = 0.05$)	$C_p = 0.5$	20	33	50	100
	$C_p = 1.0$	24	44	80	400
Class 2 ($C = 0.1$)	$C_p = 0.5$	13	17	20	25
	$C_p = 1.0$	20	33	50	100
Class 3 ($C = 0.2$)	$C_p = 0.5$	5	6	6	6
	$C_p = 1.0$	10	12	14	16

that some areas probably are ‘good’ and others ‘not so good’. This can be used to improve the precision by *stratification*. In Fig. 8 the target area is mapped and categorized into two biotope types, of which one is assumed to have lower density (or, strictly, lower spatial variation) and the other higher. In Fig. 8a, sections 1–16 are the ‘good’ and sections 17–43 the ‘bad’ biotope. The target area ($N = 43$) is thus stratified into stratum 1 ($N_1 = 16$) and stratum 2 ($N_2 = 27$).

We found above that it would take about $n = 26$ to reach Class 2 in this hypothetical stream. To make judgement on how many from stratum 1 and from stratum 2, we need to know the stratum sizes N_h and Standard Deviation SD_h . Further, as the cost of sampling one such unit may vary between the strata, this cost c_h is also of interest. One way to allocate the sampling effort is to choose

$$n_h \text{ proportional to } SD_h / \sqrt{c_h} \quad (19)$$

As, however, SD_h seems to be proportional to the mean density \bar{y} (see e.g. Tab. 3), and if c_h is similar in each stratum, (19) is reduced to

$$n_h \text{ proportional to } N_h \bar{y}_h \quad (20)$$

Thus, as an example, if we have reason to assume that the mean density in stratum 1 in Fig. 8a is about twice as large as in stratum 2, then from (20) we find that

$$\frac{n_1}{n_2} = \frac{16 \cdot 2}{27 \cdot 1} = 1.19$$

As $n_1 + n_2$ in this case was about 26, it would be appropriate to try a sample size of 14 sections from stratum 1 and 12 from stratum 2.

We now recall that the total sample size n required to reach a specific precision was calculated ignoring the effect of stratification (eq. 18). In reality, a somewhat smaller sample size may be sufficient. There are methods to estimate the n value required for a given precision level in the

case of stratified sampling (see e.g. Cochran, 1963; p. 96), corresponding to eq. (18). However, as we seldom know very much about how the strata differ with respect to spatial variation, the crude way outlined above may be sufficient.

The final question is the number of strata. As the methods of stock assessment proposed below may require both an N_h value not too small and a sample size n_h not too small, 2 or possibly 3 strata may be practicable. In theory, a far reaching stratification may pay if the criterion for stratification is efficient.

The selection of sampling areas and methods of population estimation

There are several ways of selecting the sampling areas in each stratum, and these ways may lead to different methods of population estimation. Hankin (1984) has recently treated these questions with special reference to small streams, and some of the considerations below are based on this paper.

The notation is the following:

N	total number of areas (sections) in a stratum or target area.
n	number of areas (sections) in a sample.
y_i	population size in area i , estimated as \hat{y}_i by e.g. the methods proposed in the previous section.
$V(\hat{y}_i)$	sampling variance of \hat{y}_i , estimated as $\hat{V}(\hat{y}_i)$, e.g. by the methods proposed in the previous section.
Y	total population size in the stratum or target area; estimate denoted \hat{Y} .
$\bar{y} = Y/N$	mean population size per area, estimated as
	$\hat{\bar{y}} = \left(\sum^n \hat{y}_i \right) / n$
m_i	size (usually area) of a area (section) i
M	total size (usually area) of the stratum or target area

$\bar{y}_i = y_i/m_i$ population density in a unit i , estimated as

$$\hat{\bar{y}}_i = \hat{y}_i/\hat{m}_i$$

$\bar{Y} = Y/M$ mean population density in the stratum or target area, estimated as

$$\hat{\bar{Y}} = \frac{\sum y_i}{\sum m_i}$$

$P_i = m_i/M$ probability of selecting unit i when using proportional probability sampling with replacement.

This section is organized in the following way. First, 3 general methods of total stock assessment are outlined and exemplified without much reference to their limitations. Then we continue with a discussion on how to estimate population *changes* rather than population size; this is often a main goal. Finally, the application of the methods proposed are discussed with special reference to large streams.

Methods based on simple random sampling (SRS) within strata

Regardless whether the areas are of equal or unequal size, one way to obtain a sample is to use simple random sampling. This is usually carried out by numbering all the N sections and then using a table of random numbers drawing a sample of size n . The population size y_i in each of these n sections is then estimated by electro-fishing, e.g. by some of the methods proposed above, as \hat{y}_i with a sampling variance $\hat{V}(\hat{y}_i)$.

If sections of (approximately) *equal size* (e.g. length) are used, the following method can be employed to estimate total population Y .

Compute the mean per section as

$$\hat{\bar{y}} = (\hat{y}_1 + \hat{y}_2 + \dots + \hat{y}_n)/n = \frac{\sum \hat{y}_i}{n}$$

and the estimated (spatial) variance between the areas in the usual way as

$$\hat{V}(\hat{\bar{y}}) = \frac{\sum (\hat{y}_i - \hat{\bar{y}})^2}{n - 1}$$

The total population in the stratum is then estimated as

$$\hat{Y} = N \hat{\bar{y}} \quad (21)$$

and the sampling variance $V(\hat{Y})$ of \hat{Y} as

$$\hat{V}(\hat{Y}) = \frac{N}{n} (N - n) \hat{V}(\hat{\bar{y}}) + \frac{N}{n} \sum \hat{V}(\hat{y}_i) \quad (22)$$

$SE(\hat{Y})$ is estimated as the square root of this expression.

This method will be referred to as SRS estimation without auxiliary variable.

In eq. (22), the first term is the error generated by the spatial variation of the fish population, and the second the additional error due to the fact that each y_i is estimated, not known.

If more than 1 stratum is used, the total population in the target area is the sum of the total populations in each stratum. As the sampling variances are also additive, this leads to

$$\hat{Y}_{\text{tot}} = \sum^h \hat{Y}_j$$

where h is the number of strata and Y_j the total population in the j :th stratum, and

$$\hat{V}(\hat{Y}_{\text{tot}}) = \sum^h \hat{V}(\hat{Y}_j)$$

As usually, $SE(\hat{Y}_{\text{tot}})$ is the square root of $\hat{V}(\hat{Y}_{\text{tot}})$.

Example 5. 7 sections of approximately equal length ($n = 7$) were drawn at random from a stratum with $N = 37$. The populations y_i were estimated using 3 removals and applying eq. (11) and (8). The input data c_1, c_2, c_3 and the result is then:

i	c_1	c_2	c_3	\hat{y}_i	$\hat{V}(\hat{y}_i)$
1	178	31	7	217.4	1.76
2	69	18	7	96.5	4.35
3	107	13	5	125.6	0.68
4	88	26	6	122.6	4.20
5	104	27	9	143.1	5.19
6	111	24	7	143.9	2.68
7	28	8	3	40.2	2.22

$$\hat{y} = \left(\sum^n \hat{y}_i \right) / n = 127.04$$

$$\hat{V}(\hat{y}) = 2867.1$$

$$\sum^n \hat{V}(\hat{y}_i) = 21.08$$

$$\hat{Y} = 37 \cdot 127.04 = 4700$$

$$\begin{aligned} \hat{V}(\hat{Y}) &= \frac{37}{7} (37 - 7) 2867.1 + \frac{37}{7} 21.08 = \\ &= 454640 + 111 = 454751 \end{aligned}$$

$$SE(\hat{Y}) = \sqrt{454751} = 674$$

The coefficient of variation $C = 674/4700 = 0.14$

Note that the last term in $\hat{V}(\hat{Y})$ is extremely small (0.02% of the total variance) and can safely be ignored. This will probably be the case in many cases when p is of 'normal' magnitude and 3 removals applied. If 2 removals are carried out in the case above, the last term is still negligible because the p is large.

If the sampling sections are of *unequal size*, formulas (21)–(22) will still hold. If however, they differ greatly, $\hat{V}(\hat{Y})$ in eq. (22) will be large and thus the sampling variance large. In this case, a better method is to include the size (e.g. area) m_i in the calculation. If so, and if still using simple random sampling within strata, this leads to a *ratio estimation* of the population size. We call this method SRS ratio estimation or SRS with auxiliary variable since m_i is also included. In addition to the size m_i of the sections in the sample, the total size (area) M of the stratum must also be known. With the notation above, the total fish population in the stratum is estimated as

$$\hat{Y} = M \sum^n \hat{y}_i / \sum^n m_i \quad (23)$$

and the population density (e.g. per 100 m²) as

$$\hat{\bar{Y}} = \sum^n \hat{y}_i / \sum^n m_i \quad (23')$$

As the ratio estimation is biased (in the order of a factor $1/n$), the precision of \hat{Y} might be expressed as the Mean Square Error of (\hat{Y}) , $MSE(\hat{Y})$, rather than the variance $V(\hat{Y})$. The $MSE(\hat{Y})$ is larger than $V(\hat{Y})$ for biased estimates since it also includes the (squared) bias. In practice, the $MSE(\hat{Y})$ for the ratio estimate above can be compared with the variance $V(\hat{Y})$ of the foregoing method (eq. 22). An estimate of $MSE(\hat{Y})$ is

$$M\hat{S}E(\hat{Y}) = \frac{N(N-n)}{n(n-1)} \sum^n m_i^2 (\hat{y}_i - \hat{y}) + \frac{N}{n} \sum^n \hat{V}(y_i) \quad (24)$$

The MSE for the population density \bar{Y} is

$$M\hat{S}E(\hat{\bar{Y}}) = M\hat{S}E(\hat{Y})/M \quad (24')$$

Example 6. The data from example 5 are used (although the sample size $n = 7$ is too small for this method, see below), together with data on the area m_i of these sections. We assume that the total stratum area is 10000 m². The result is shown on the next page.

Using these figures we find, from (23), $\hat{Y} = 10000 \cdot 889.3/1874 = 4745$, and from (23'),

mean density $\hat{\bar{Y}} = 889.3/1874 = 0.4745$ per m².

$$\begin{aligned} \text{From (24), } M\hat{S}E(\hat{Y}) &= \frac{37 \cdot 30}{7 \cdot 6} 11853 + \frac{37}{7} 21.08 \\ &= 313369 \end{aligned}$$

$\sqrt{M\hat{S}E(\hat{Y})} = 560$, which can be compared with $SE(\hat{Y}) = 674$ in example 5.

As in the previous method, the ratio estimators can be added in the case of more than one stratum.

Methods based on proportional probability sampling (PPS)

If areas of *unequal size* are chosen, another way of selecting a sample of such areas is to use sampling probabilities proportional to the size

i	\hat{y}_i	$\hat{V}(\hat{y}_i)$	m_i	$\hat{y}_i = \hat{y}_i/m_i$	$m_i^2(\hat{y}_i - \hat{y})^2$
1	217.4	1.76	290	0.750	6674.4
2	96.5	4.35	319	0.303	2780.0
3	125.6	0.68	275	0.457	9.63
4	122.6	4.20	271	0.452	19.49
5	143.1	5.19	342	0.418	295.8
6	143.9	2.68	231	0.623	1277.3
7	40.2	2.22	146	0.275	796.4
$\hat{y} = \sum^n \hat{y}_i/n$				0.468 29	
$\sum^n \hat{y}_i$		889.3			
$\sum^n \hat{V}(\hat{y}_i)$		21.08			
$\sum^n m_i$			1874		
$\sum^n m_i^2(\hat{y} - \hat{y})^2$					11 853

(area) of the areas (Appendix 2). We therefore need to know the size (area) of *all* the N areas in the stratum (not only the total area M as in the previous method), so in practice probability sampling is restricted to streams in which N is not too large.

The simplest version is proportional probability sampling *with replacement*. This means that each section is drawn independently, and that the same section may be included more than once in a sample. This drawback is counterbalanced by the fact that the corresponding sampling *without replacement* leads to estimators which have to be calculated with computer aid. With replacement, however, the calculations are very simple. With the notation above ($M =$ total stratum area, and $p_i = m_i/M$), an estimator of total population size is

$$\hat{Y} = (1/n) \sum^n \hat{y}_i/p_i = \text{mean of } \hat{y}_i/p_i \quad (25)$$

and the sampling variance $V(\hat{Y})$ of \hat{Y}

$$\hat{V}(\hat{Y}) = (1/n) \hat{V}(\hat{y}_i/p_i) \quad (26)$$

where $\hat{V}(\hat{y}_i/p_i) =$ the (spatial) variance of \hat{y}_i/p_i , usually calculated as

$$\frac{\sum^n (\hat{y}_i/p_i - \hat{Y})^2}{n - 1}$$

Example 7. The following \hat{y}_i and m_i values were obtained from 7 sections in a stream, selected by proportional probability sampling with replacement. If $M = 10000$, the result is

i	\hat{y}_i	m_i	$p_i = m_i/M$	\hat{y}_i/p_i
1	39.0	52	0.0052	7 500
2	24.2	80	0.0080	3 025
3	58.0	127	0.0127	4 567
4	105.3	233	0.0233	4 519
5	84.4	202	0.0202	4 178
6	109.0	175	0.0175	6 229
7	27.5	100	0.0100	2 750

Mean of (\hat{y}_i/p_i)	4 681
Variance of (\hat{y}_i/p_i)	2 850 797

Thus, $\hat{Y} = 4681$ and $S\hat{E}(\hat{Y}) = \sqrt{2850797/7} = 638$

Note that it is not necessary to estimate $V(\hat{y}_i)$; they are automatically included. If population density is to be estimated, just divide \hat{Y} and $S\hat{E}(\hat{Y})$ by M .

Estimation of population changes

So far we have only discussed some methods to estimate total stock or density. Both in fishery management and environment monitoring, however, population change is often of greater interest than absolute values.

We can use all methods above to estimate the *absolute population change* $D = X - Y$, where Y is the population size in one occasion and X in another. To do this, however, the best method is probably to use as input variables $\hat{d}_i = \hat{x}_i - \hat{y}_i$ instead of \hat{y}_i , and instead of $\hat{V}(\hat{y}_i)$ the sum $\hat{V}(\hat{x}_i) + V(\hat{y}_i)$.

The result is an estimate \hat{D} and its variance $\hat{V}(\hat{D})$ or Standard Error $S\hat{E}(\hat{D})$. In this case the comparison is based on 'paired' observations, viz. the same sections on each occasion. This design is often the best one when the main aim is to monitor changes, and the reason is that there is often a positive correlation between \hat{y} and \hat{x} ('good' sections in one year are often 'better' than the average even in the following year). This tends to reduce the (spatial) variance of the \hat{d}_i values and therefore also the sampling error of \hat{D} . There are two practical consequences of this:

1. The gain in precision is probably larger when using the SRS design with no auxiliary variable (Eqs. (21–22)), than if SRS with an auxiliary variable is used (egs. (23–24)) or in the case of PPS (eqs. (25–26)). In practice this means that SRS without the use of an auxiliary variable, being the cheapest method, may perform as well as the other two methods and should be tried when estimation of absolute population change is the main aim.
2. When using SRS without an auxiliary variable, the gain in precision by using paired observations depends on both the variances $V(\hat{y})$ and $V(\hat{x})$ and on the correlation between x and y . Using the data on which Table 3 is based,

Table 5. Sample size n required to reach a given precision class (see 3.3.) for various combinations of coefficients of correlation r and total number of units N . $C_p = 0.8$ in all cases. Paired observations assumed. *Sample size and precision classes, paired data.*

		N = 25	N = 50	N = 100	N = ∞
Class 1	r = 0	22	38	60	160
	r = 0.6	19	29	40	64
	r = 0.8	16	21	27	34
Class 2	r = 0	16	22	26	34
	r = 0.6	11	13	15	17
	r = 0.8	9	10	11	11
Class 3	r = 0	10	12	14	14
	r = 0.6	8	9	9	9
	r = 0.8	6	7	7	7

covering a wide range of stream types, we found strikingly similar correlation coefficients r between population size per section year 1 and year 2 ($r = 0.63$ – 0.79) for salmon and trout older than one summer. Further, if we assume a C_p value of 0.8, we can make a crude calculation of the sample size required to reach precision class 1–3 in the case of paired observation. The result (Table 5) can be compared with the sample sizes in Table 4. This comparison shows that considerably smaller sample sizes n are required to 'discover' population changes of a given magnitude (Table 4) than to 'discover' differences between populations (Table 3). It appears that a sample size of about 15 would be sufficient to reach Class 2 even in large streams (N large).

To test whether an observed difference \hat{D} is statistically significant, the safest way is to use a non-parametric test, e.g. Wilcoxon match-paired signed-ranks test, which is powerful but very simple to use (see e.g. Siegel, 1958; p. 75).

Finally, the *relative population change* $R = X/Y$ (e.g. finite survival) is often of interest. As pointed out by Youngs and Robson (1978), however, the sampling variance of such a ratio 'is much more complex and has not been dealt with to any greater extent in fishery literature'. We therefore know little about sampling designs where the main aim

is to estimate relative population changes. Bohlin (1981) suggested the following method, applied to SRS with no auxiliary variable:

$$\hat{R} = \hat{X}/\hat{Y} \quad (27)$$

where \hat{X} and \hat{Y} is from eq. (21). The approximate sampling variance $\hat{V}(\hat{R})$ of \hat{R} is

$$\hat{V}(\hat{R}) = \frac{\hat{V}(\hat{Y})\hat{X}^2 + \hat{V}(\hat{X})\hat{Y}^2 - 2r\sqrt{\hat{V}(\hat{Y})\hat{V}(\hat{X})} \cdot \hat{X}\hat{Y}}{X^4} \quad (28)$$

Here, $\hat{V}(\hat{Y})$ and $\hat{V}(\hat{X})$ is from eq. (22) and r is the coefficient of correlation between \hat{x} and \hat{y} , calculated in the usual way. Eq. (28) is approximate even for large samples. Note that a large positive correlation will increase the precision substantially.

On the choice of sampling methods with special reference to large streams

Let us first recall the information required to apply the three main methods proposed:

SRS – no auxiliary variable: N

SRS – auxiliary variable used: N , total area M , section size m_i for the n sections in the sample

PPS – Section size m_i for *all* N sections.

For large streams (N large) the PPS methods will thus be impractical, so the options are the SRS methods. The applications of these methods to large streams, however, is not self-evident. In many cases, electrofishing is possible only in some areas, mainly along banks and in other shallow areas where the current is not excessive. In order to obtain the M value, the whole stream has to be visited and measured with respect to area and depth relations. Although this can be simplified using e.g. aerial photography it may still be a formidable task. If so, this leaves us to the least precise of the methods, the SRS without auxiliary variables. A practical compromise may be the following in the case of large streams:

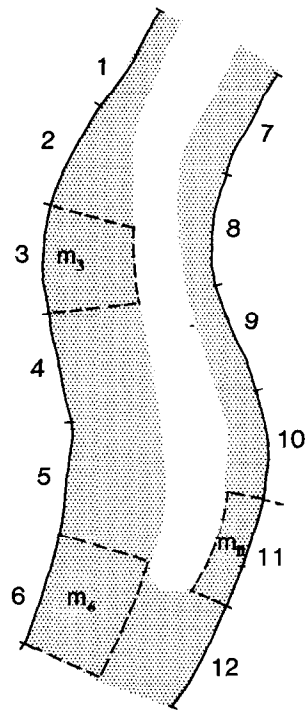


Fig. 9. A suitable sampling design in a large stream may be to divide the stream into areas of approximately equal length using a map, in this case $N = 12$ sections. A sample of n sections (here $n = 3$) is drawn by simple random sampling. The areas m_i in which electrofishing is possible (stippled) is measured. For some estimates the total stippled area M must be known (see text).

Using a reliable map, the stream is divided into N sections of approximately equal length (see Fig. 9) from which are drawn a random sample of n sections after stratification. As the 'functional' width of the latter may vary greatly depending on depth etc., the area m_i of the random sample are also measured. The population density within the stratum or target area is then estimated from eq. (23'). The sampling error of this estimate, however, cannot be estimated unless M is known (eq. 24'), so if an estimate of the sampling error is important M has to be measured. In many cases, however, it may be more useful to estimate population *change* rather than absolute density. As stated previously, the SRS without auxiliary variable may work well in this case provided a fair correlation between x and y , so M may not have

to be known. If so, use eqs. (21–22), with y replaced by $d = x - y$, to estimate absolute change and eqs. (27–28) to estimate relative changes. To summarize, it may be possible to estimate both population density and population changes with reasonable precision, even in large streams, if the sample size is large enough, but the precision of the population density estimate may be hard to obtain if M is difficult to measure. Population density estimates from different streams should, however, be compared with care.

In small streams there may be a possibility to choose between all the three methods proposed above. As stated above, a design with varying section size is especially valuable if the 'natural' biotope units are of a practicable size. Hankin (1984) made the following general recommendations:

- (1) If N is small (say 20 or less), neither the SRS ratio estimation or the PPS with replacement can be recommended. This leaves us to either the SRS without use of auxiliary variable or to the PPS without replacement.
- (2) If N is large (say 50 or more), the choice is less clearcut. If N is very large (say 100 or more), the SRS ratio estimation may be recommended if n is not too small (say 12 or more), and the PPS with replacement if n is smaller.

As the sample size required usually is more than 12 and N often moderate or large, the SRS ratio method appears to be useful, especially as the result always can be directly compared with SRS without auxiliary variable. As proposed above concerning the sampling design of large streams, a 'mixed' strategy may be useful even in small streams, using the SRS ratio estimation for density or total stock and SRS without auxiliary variable for population changes.

Electrofishing for other purposes

When applied properly, longterm effects of electrofishing on fish are small. The method is therefore suitable for catching fish to be kept alive for

further experimentation. Non pulsed direct current should then be used.

Electrofishing may be used in situations other than quantitative population estimates. In order to ensure inclusion of a given fish species, it is however, necessary to have certain degree of knowledge of that species' habitat preferences and selectivity when carrying out electrofishing. When documenting the occurrence of different fish species in a watercourse, it is essential that all types of habitat (water velocities, depths, substrates, etc.), are covered, while at the same time making sure that those species are catchable with an electrofishing apparatus. As *Thymallus thymallus* often is difficult to catch by electrofishing, it may be necessary to include other equipment such as sport fishing gear or nets. In such cases electrofishing is carried out when water levels are lowest.

In most studies it is necessary that specimens are preserved for later examination. Experience from Norway (as well as other places) has shown that growth of presmolt salmon varies considerably in different parts of the same river. It is therefore essential that material for growth analysis is collected from more than one location in the river. The distance between collection stations should never exceed ten kilometers. Repeated electrofishing at short intervals should be avoided because frequent electroshocking (< 3 months) are likely to underestimate growth rates (Gatz *et al.*, 1986).

Dense populations of small, stationary trout or other fish species are often found in streams and small rivers. Fish required for release in other rivers may be obtained by using electrofishing equipment. Experiments conducted in Norway have demonstrated that it is possible to catch 100–200 trout per hour of a size between 5 and 20 centimeters in streams with dense fish populations. The advantage of this kind of fishing is that large fish, capable of surviving, are caught at the same time that an overcrowded trout population is reduced. Fishing should be carried out at low temperatures, in order to ensure that fish are transported without high mortality. In order to avoid spreading of undesirable fish species, dis-

eases and parasites, qualified persons should control and identify release specimens.

The electrofishing apparatus is extremely efficient for catching trout and salmon parent fish in smaller rivers and streams. Highest efficiency is attained by using a boat. In deep waters it may be necessary to lengthen anodes and cathodes. High voltage should be avoided as large fish are easily damaged or killed when exposed to long lasting or strong electrical current.

Electrofishing in practice

There is no principal difference between electrofishing in lakes and streams, and sampling design is similar. The design of equipment and performance of fishing is often slightly modified depending on differences in habitat and fish behaviour.

Electrofishing in streams

The fishing operation should be performed by a team of at least 2 persons. The fisherman handles the anode and is usually equipped with a hand net for catching. The cooperator is responsible for the handling of the catch and may also take part in collection. The fishing efficiency, both with respect to time and accuracy, is closely related to the experience of the team, and quantitative fishing should only be carried out by qualified personnel.

The fishing is carried out in an upstream direction. If the removal method is used, it is essential to work in a standardized manner. The time spent is of little relevance; the main thing is to cover the whole area in a systematic way. A time lapse of at least half an hour between the removals is recommended.

In large streams and rivers the area possible for electrofishing is restricted by depth and rate of flow to certain parts, e.g. along the banks. As discussed in Chapter 4, this has consequences on the possibility of estimating population size. One reason is that the catchability of fish within a

sampling area gradually decreases with increasing depth, which may yield a negative bias. Further, flight effects may cause displacement of fish from the area. If the time lapse between fishings is prolonged, fish may also immigrate, which further complicates the evaluation.

The use of blocking nets to avoid some of the above effects is a matter of some controversy. In a small stream where the cross section is much smaller than the length of the area, the use of blocking nets is probably not necessary when fishing for territorial salmonids, as we have no indications of fish concentrations in the vicinity of the nets. In large streams blocking nets are sometimes used. The transportation and installation of these is usually laborious, and the advantage may be counterbalanced by the fleeing effect of fish while installing the nets. Further, in large streams the object is usually by necessity restricted to estimation of population change, and this change is probably not estimated most accurately by the use of blocking nets. In most cases, therefore, the use of nets is not recommended. In large streams when blocking nets are not used, the study area must be marked to ensure that the same area is fished each time.

Other complications frequently encountered in large streams are caused by a varying water level. After a rapid rise it may take some days before near shore areas are reoccupied by fish. Further, the physical conditions (depth, substrate, flow) of a stream section may vary widely with the water level which may effect both the population and its catchability. We therefore recommend quantitative fishing only after a period of stable flow, and, especially when following population changes, at similar water levels.

In addition to the water level there are other environmental factors influencing catchability or accuracy which may vary with time, e.g. temperature, turbidity etc. When monitoring population change the fishing should therefore be carried out under similar conditions in these respects as well.

Electrofishing in lakes

In open water areas of depths greater than the attraction radius (appr. 1 m) electrofishing is generally unsuccessful irrespective of the abundance of fish. This is probably due to flight reactions. Electrofishing is ineffective when the transparency of the water is less than the attraction radius, and is almost impossible when the transparency is less than the immobilisation radius (app. 0.3–0.5 m).

In shallow water and/or in vegetated areas electrofishing is possible and might, depending on fish species and habitat, be very efficient. In suitable cover from vegetation or bottom substrates most fish remain immobile even when boats carrying noisy and vibrating equipment are close. Fish generally do not show flight reactions until in contact with the repelling zone of the anodic field.

Electrofishing in lakes is also useful for population estimates by mark-recapture methods. To reduce the inevitable effects of selectivity (with respect to habitat and fish size), recapture should be performed by other methods (e.g. gill nets, fyke nets or by trawling). It is advisable to check whether more or less closed subpopulations exist in e.g. litoral and pelagic areas. When calculating the population size, different size classes should be treated separately. By comparing the catch and the abundance of fish in different size classes the selectivity of the fishing method can be estimated. The abundance of fish in size classes with few or no recaptures can then be estimated by interpolation of the selectivity (catch per effort/population size) of adjacent size classes.

For some species and in some habitats the catchability is high and the removal method can be applied for population estimates. It is often useful to subdivide the litoral zone with respect to habitat (e.g. sand, gravel, stones, submerged vegetation, emerged vegetation). In small lakes (< 20 ha) the total litoral zone can often be fished in one day. In larger lakes the litoral zone should be thoroughly subdivided into different relevant habitats to facilitate subsampling. Movements of fish between habitats is often negligible during day-time.

All species occurring in the litoral zone can be caught by electrofishing. Bottom dwelling species like cottids, ruffe, *Acerina cernua*, gudgeon, *Gobio gobio*, and crayfishes are generally vulnerable to electrofishing. This is also true for species like perch, *Perca fluviatilis*, and for some cyprinids like e.g. *Phoxinus phoxinus* and rudd, *Scardinius erythrophthalmus*. Pike, *Esox lucius*, and large cyprinids like tench, *Tinca tinca* and crucian carp, *Carassius carassius* can be found litorally during all seasons, but especially larger individuals are most easily caught during spawning. Pelagic species like roach, *Rutilus rutilus*, and bream, *Abramis brama*, can be caught in very high numbers during schooling in litoral areas in late autumn and winter.

Litoral fishing in shallow water can be performed by walking along the shore line. This method is often the only one possible for central and inner parts of vegetation. In most cases, however, it is more efficient and less strenuous to fish by boat. It is then also possible to use heavier and more efficient equipment.

When using gasoline engines it is in most cases, both for practical and security reasons, advisable to place the engine in a small, separate boat tied to a larger one. The latter is then used by the working team and for the equipment necessary for handling the fish. If the fish are to be marked, an operational team should consist of three persons; one managing the boat(s), one fishing and one measuring and marking the fish. In this way the fish can be measured and marked before the effects of the electronarcosis have disappeared, which facilitates handling. Most fish can then be replaced in approximately the same habitat where they were caught. In cases where the whole population is simultaneously vulnerable to electrofishing the mark-recapture method can be substituted by multiple mark-recapture. The validity of the assumption of random sampling on a day to day basis inherent in this method must however be proven.

Safety, training and disinfection

Introduction

Even a weak electric field through the body might result in heart failure. As voltages of more than 200 V usually are required for efficient electro-fishing, it is important to realize the potential danger of electrofishing operations. Moisture may cause perilous leakage of current to control boxes, frames or to the anode handle, and accidental exposure to the anodic or cathodic fields may be fatal. To reduce these risks, proper construction of equipment and adequate training of personnel is imperative.

Equipment

The equipment should be constructed and approved according to national standards. Alternating current (AC) is extremely dangerous and should not be used as output voltage. If an AC power unit is used the current must therefore be transformed to non-pulsed or pulsed DC via a control box.

All components of the equipment must be suitable for exposure to outdoor and wet environments. Special attention should be paid to the standard of the control box enclosure, terminals, plugs, sockets, cables and the anode handle. In addition, the robustness, construction and quality of the mounting is of primary importance for safety. The risk of current leakage is reduced if the control box is provided with a ventilated insulating enclosure. For portable equipment proper insulation between the frame and the power unit/control box is especially important.

Output from the power unit and the control box should be provided with indicators showing when the units are energised and when power is available to the electrode connectors.

Cables and connectors should be insulated with a rated voltage in excess of the output voltage from the control box.

The anode should be provided by a dead-man switch, operating through a low voltage secondary

circuit. This switch is often a weak point as repeated exposure to moisture may cause breakdown. The Norwegian switch (Paulsen type), which is closed and operated by a magnet, appears to be a good solution.

Dip net handles and fish containers – if placed in the water – must be made of non-conducting material.

All equipment used must be checked for mechanical and electrical faults at intervals according to the degree and conditions of use, and at least annually.

Operation

The anodic as well as the cathodic fields are potentially dangerous.

The cathodic field must not be left unguarded during the fishing operation. Holding nets for fish must not be placed in the vicinity of the cathode.

Only first class quality waders in good condition and with efficient anti-slip soles should be used, especially in large streams. Avoid fishing in deep rapids, both for security and efficiency reasons.

To reduce the risk of current leakage, electro-fishing should not be performed in rainy weather. When fishing from a boat buoyance aids must be worn. The boat must be large and stable enough to accommodate the crew. We recommend boats made of non-conducting material for electro-fishing.

Electrofishing must be carried out by a team of at least two persons. An experienced team leader should be responsible for safety, first aid, equipment and protective clothing, and for safety instructions to each member of the team.

Training and permission

Permission to perform electrofishing should only be given to persons who have participated in a course comprising theory and practice of electro-fishing, including safety considerations and first aid. This course should be approved by the national fishery authorities.

Disinfection

In order to prevent spread of diseases (i.e. virus and bacteria) and parasites (e.g. *Gyrodactylus* and the crayfish plague) all the equipment (electrodes, waders, dip nets, holding nets, buckets, boats etc.) must be adequately disinfected before fishing in new areas (up-stream areas or in new catchment areas). Disinfectants approved by the national authorities should be used. Formalin (2% solution) iodophor solution (50–100 ppm free iodine) and complete drying are normally sufficient.

Conclusions and recommendations concerning the use of electrofishing for studies of fish populations

Equipment

- Do not use alternating current.
- Use high output voltage (> 500 V) and weak generators (< 1 kW) when fishing in low conductivity waters (< 100 μS) and low voltage (< 300 V) and strong generators (> 2 kW) in high conductivity waters (conductivity > 500 μS ; cfr. Fig. 6).
- Use gasoline generators in high conductivity waters. Batteries are sufficient in low conductivity waters (< 75 μS).
- Use non pulsed direct current when the target animals are hidden in dense vegetation, under stones or in the mud, and when fishing in turbid waters, or at low temperatures.
- Use pulsed direct current when fishing in slow flowing streams and open water areas of lakes.
- Use condenser discharge pulses when the effect of the power unit is restricted (e.g. because of high water conductivity or transportation problems).
- When using pulsed direct current, use frequencies over 50 Hz and a pulse length of more than 1 ms. If the attraction radius is too small, increase frequency and/or pulse length.
- If possible, the radius of the ring shaped anode should be 40 cm or larger. In high conductivity waters, use non-corrosive alloys for the anode, e.g. aluminium.
- For stationary equipment, cathods made of iron netting are recommended. Wire cathods are suitable for portable equipment.
- The area of the cathode should be at least three times as large as that of the anode.
- For recommendations concerning security, see the previous section.

Quantitative electrofishing for different fish species

- Realize that the behaviour of the fish species and the biotope type in their habitat determine their catchability and thereby the possibility for estimating the population density with accuracy and precision. As there are only a few studies in which population estimates based on electrofishing have been checked against populations of known size, little is known about which fish species are successfully quantified by electrofishing. As a rule, the following can be stated:
 - For territorial salmonids, e.g. Atlantic salmon, brown trout and stream dwelling arctic charr, electrofishing is often successfully applied.
 - Bottom dwellers, e.g. eel, sculpins and burbot, generally have a lower catchability, probably resulting in a larger but unknown underestimation than in the preceding species.
 - Schooling species, e.g. most cyprinids, often have a low and unpredictable catchability. Absolute population estimates of these species are therefore often of doubtful value.
 - Some pelagic or semipelagic species have a tendency to avoid the electric field and might therefore often be hard to quantify, e.g. grayling.
 - For other species, the estimated catchability may be large, but critical studies on the relation between estimated and real population size are lacking.

Planning of electrofishing surveys in streams

- Specify the object of the investigation with special reference to the target area and whether estimation of population size (density) or population change is the main aim. The target area is the total water area you wish to make statements about and in which quantitative electrofishing is possible.
- If the target area is so large that a total sampling is impractical, you have to decide upon the number and size of sampling areas in the target area, e.g. by following the recommendations below.
- Map the target area with respect to biotope type of relevance for the population density and group the sampling areas into two or possibly more density classes (strata). If the biotope is homogeneous, grouping (stratifications) may not be required.
- Divide each stratum into sampling areas of suitable size. The size of these can vary according to biotope variation, e.g. in small streams (Fig. 8b), or be of equal length (Fig. 8a). In waters with homogeneous biotope type, sampling areas of equal length may be the most practical (Fig. 9).
- In order to optimize the size of the sampling area, use the following guidelines:
 - The final computations are usually more accurate if the total number N of the sampling areas is the target area is not too small (in the magnitude of some tens). It may therefore be convenient to choose small sampling areas if the target area is small.
 - The risk of fish displacement from a sampling area increases with the perimeter/surface ratio. In large streams and the littoral of lakes it might therefore be better to choose larger areas than in small streams.
 - The final calculations are usually simpler and the estimates more precise if the size of the sampling area is chosen so that its population is 50 or more.
- From the aim of the investigation, state the approximate precision requirement, e.g. according to the precision classes suggested above.
 - For a preliminary determination of the number (n) of sampling areas required to reach this precision, use the N value obtained (the total number of sampling areas within the *target area*) and consult Table 4 if population size or density is the main aim, and Table 5 if population change is the main aim. As an example, if $N = 100$ and Class 2 required, a sample size of 20–50 sampling areas may be tried if population size (density) is the target, and 11–15 in the case of estimating population change. If field data are available, eq. (18) may be used to calculate the sample size required.
 - If you have stratified the target area, distribute the n sampling areas so that large, high density strata will get a larger fraction of these than small, low density strata.
 - From each stratum, select the sample required by simple random sampling (SRS) or proportional probability sampling (PPS).

Performance of electrofishing in streams

- The removal method is usually sufficient. Mark–recapture methods will in some circumstances yield more accurate estimates.
- If the removal method is used, at least 3 removals in each sampling area is recommended. If the estimated catchability is lower than about 0.5, make more than 3 removals.
- For each removal, each species and size class is noted separately.
- Make a break between the removals, at least 30 min.
- Work in an up-stream direction.
- Do not disturb the sampling area before fishing.
- Generally, the use of block nets is not necessary.
- If estimation of population change in time is the main aim, the fishing should be carried out during similar conditions (type of gear, flow, turbidity, temperature, time of the day etc.).
- Avoid fishing during periods of high or rapidly changing flow, especially in large streams.
- Avoid fishing when fish are inactive (e.g. in low temperature) or schooling.

- Only trained personnel should perform quantitative electrofishing.

Performance of electrofishing in lakes

- Use electrofishing in shallow and vegetated areas at transparencies higher than 1 m.
- Fish by boat and place gasoline engines in a separate boat.
- Pursue to handle the fish before it has recovered from the electronarcosis.
- For population estimates use mark-recapture methods and recapture the fish by methods other than electrofishing.

Calculation of population estimates

- In the case of the removal method, use the appropriate maximum likelihood estimator.
- Separate estimates for each species and size class are made.
- If the population in a sampling area is smaller than about 50, or if fewer than 3 removals have been carried out, use the ‘pooling’ method (cfr. examples 3 and 4).
- The smallest size class may be subjected to large underestimation. For salmonids, special attention is called for when a large population fraction is smaller than about 50 mm.
- In large rivers, where the area in which quantitative electrofishing only is possible is small relative to the total stream area, estimation of total population size is not possible by this method.

Evaluation of results

- Generally, estimated population size or density is lower than true population size (density).
- A low estimated catchability is a warning sign, as the underestimation in this case probably is large. Observe, however, that a large estimated catchability is no guarantee that the underestimation is low.

- The degree of underestimation may vary with fish species, fish size, fishing gear and fishing conditions, e.g. biotope, temperature, water flow, turbidity.
- Comparison of population densities can therefore only be relevant in specific situation (same or similar fish species, biotope, gear etc.).
- In large rivers, population change in selected areas over time should be estimated rather than assessment of total population.

Recommendations concerning safety

- Electrofishing equipment should be approved according to national standards.
- Only DC systems should be used.
- The anode should be provided with a waterproof safety control (dead-man switch) operating through a low voltage secondary circuit.
- Only trained personel should perform electrofishing.
- This training should be provided by a course, approved by the national fisheries authority.
- Permission for electrofishing should be personal on specific conditions.
- Equipment should be checked at least annually.
- Avoid fishing in rainy weather.
- For both safety and efficiency, a fishing team of two persons is the minimum requirement.
- Disinfection of equipment should be made adequate.

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Appendix 1

Derivation of equation (10)

For the 2-catch method,

$$\hat{q} = \frac{c_2}{c_1}$$

If k removals are carried out, q can be estimated from each pair of catches as

$$\hat{q}_i = \frac{c_{i+1}}{c_i}$$

yielding $(k - 1)$ estimates of q . q can then be estimated as the weighted mean of these estimates. The best result is obtained if the weighting factor is inversely proportional to the variance $V(q_i)$. As

$$V(q_i) = V(p_i)$$

and as $V(p_i)$ is inversely proportional to y_i (see e.g. eq. (9)) and, hence, inversely proportional to c_i , the weighting factor for q_i is c_i . The weighted mean thus becomes

$$\begin{aligned} \hat{q} &= \frac{\hat{q}_1 c_1 + \hat{q}_2 c_2 + \dots + \hat{q}_{k-1} c_{k-1}}{c_1 + c_2 + \dots + c_{k-1}} = \\ &= \frac{c_2 + c_3 + \dots + c_k}{c_1 + c_2 + \dots + c_{k-1}} = \\ &= \frac{T - c_1}{T - c_k} \end{aligned}$$

Appendix 2

Proportional probability sampling (PPS)

Proportional probability sampling is carried out in the following way. First, list the size (area, or possibly length) m_i of all the N units. Then compute the cumulative sum of m_i and finally the 'assigned range' as in the following example with $N = 8$:

i	m_i	Σm_i	Assigned Range
1	72	72	1–72
2	100	172	73–172
3	37	209	173–209
4	212	421	210–421
5	20	441	422–441
6	91	532	442–532
7	10	542	533–542
8	150	692	543–692

To select the first unit, use a table of random numbers and pick a random number between 1 and 692. Say that this number is 301. As this number is included the 4th unit, the first sampling section is number 4. The procedure is then repeated until n units are selected.

PPS with replacement: each unit is drawn independently, so that the same unit may be included more than once.

PPS without replacement: a unit once drawn is spent; the same unit is not allowed to be included more than once.