al., 1998; Andersen, 1999), however this increase in slug populations does not always translate into higher levels of crop damage by slugs. Various reasons could account for this, including higher levels of natural predation (Symondson, *et al.*, 1996; Kromp, 1999), but the increased choice in alternatives to the crop for food is likely to play a significant role as well.

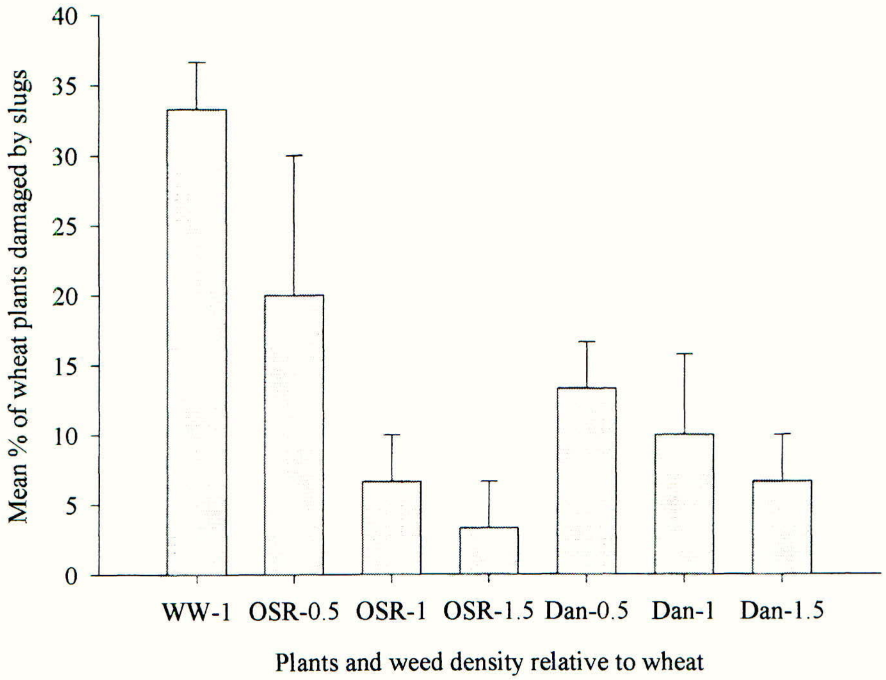

Figure 1. Mean (± SE) percentage of winter wheat (WW) plants damaged by slugs after 72 h at different densities of winter oilseed rape (OSR) and dandelion (Dan) (n=3). OSR/Dan-0.5 signifies half the plant density/m^2 of winter wheat, OSR/Dan-1 the same density, and OSR/Dan-1.5 one and a half times the density of winter wheat plants; the density of winter wheat = 318 plants/m^2.

The results from the current study indicate that the presence of specific weeds and the density at which they occur, can play a significant role in reducing the likelihood of slug damage to winter wheat and other crops. Cook, *et al.* (1997) demonstrated that slugs tend to eat the first food item they encounter, so if they are more likely to encounter a palatable weed species than the crop, then damage to the crop will be reduced. However, Frank & Barone (1999) found that when they sowed weeds in high densities with oilseed rape seedlings, the crop was only protected from serious slug damage if slug populations were low e.g. at 10 /m^2; larger slug populations of 20 /m^2 led to crop failure. It should however, be taken into account that oilseed rape itself is a preferred food for slugs ahead of wheat (see Table 1), and volunteer rape itself can be a serious weed in crops.

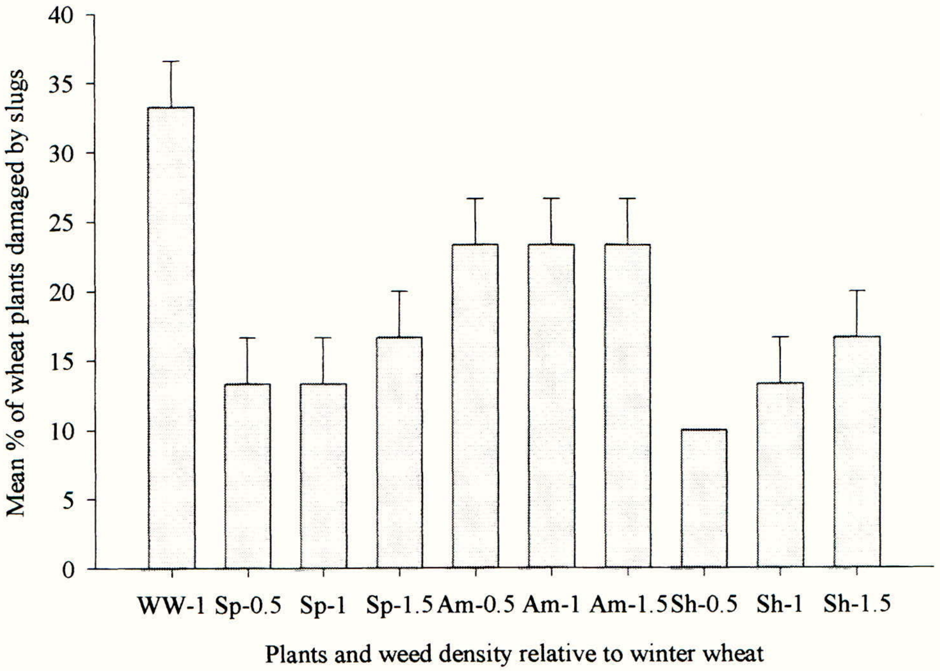

Figure 2. Mean (± SE) percentage of winter wheat plants damaged by slugs after 72h at different densities of field speedwell (Sp), annual meadow grass (Am) and shepherds purse (Sh) (n=3). See legend for Figure 1 for further explanation.

Should growers encourage (or even sow) particular weeds that are palatable to slugs in order to divert slug feeding away from crops such as winter wheat? The weeds can then be controlled by an autumn herbicide application once the crop has established and the risk from slug damage is passed. This approach may have some merit, but necessitates the assessment of the weed species present within a given field, and goes hand in hand with an assessment of slug populations, weed density, and the hope that field conditions in the autumn don't prevent access to the field for a herbicide treatment.

Studies of minimum and no-tillage systems can provide some evidence to back up the hypothesis that slug management via the use of weeds as alternative food sources can be a viable option for winter wheat growers. However, in practice a combination of approaches that utilise the conservation of natural enemies, weeds as alternative food, and targeted use of molluscicides is likely to prevail for the foreseeable future.

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Molluscicidal properties of a mixture of nicotinanilide with niclosamide

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ABSTRACT

In order to improve control of the amphibious snail *Oncomelania hupensis* Gredler which spreads schistosomiasis to buffalo and humans in China, mixtures of nicotinanilide and niclosamide were investigated via static toxicity tests and field trials. 0.4 mg/litre of a mixture of nicotinanilide and niclosamide caused 97-100 % mortality of *O. hupensis* in the lab. A field application rate of 0.4 g/m^2 gave mortality rates of 81.1-100 %. On exposure to the mixture, significantly fewer snails left the water than when the original molluscides were used independently. The mixture was 77.6 % cheaper per unit of effect than nicotinanilide

INTRODUCTION

In 2001, a World Bank report on Schistosomiasis suggested that niclosamide could be a candidate molluscicide for control of *Oncomelania hupensis hupensis*, the amphibious intermediate host of *Schistosoma japonicum*. Wide scale use in China would be expensive but it could still be valuable if used in a more efficient way. Nicotinanilide is an effective molluscicide with a low toxicity to fish. However, target snails may be stimulated to leave the water on contact with this molluscicide (WHO, 1993; Dussart, 1992). The Hubei Schistosomiasis Research Institute has screened a wide range of materials for their molluscicidal properties (eg. Xu, *et al.*, 2001; Cai, *et al.*, 2002; Wei, *et al.*, 2000 ; Wei, *et al.*, 2002). The aim of the present study was to investigate whether a mixture of nicotinanilide and niclosamide could be a useful candidate for intermediate host snail control in China.

MATERIALS AND METHODS

Nicotinanilide sulphate (NS) and Niclosamide (NCL) were obtained in the form of 50 % powders (NS - assay serial number 200107001 Hubei Zhongtian Medical Limited Company NCL - assay serial number 200105006 Zhichuan Institute of Chemical Industry). The two powders were thoroughly blended in equal proportions to form a new compound (NN). *O. hupensis* snails were collected from the flood plain of Yan-Xing County in Hubei province and washed in tap water. Only active snails were selected for testing. Controls were used in all experiments. The fish, *Gobiocypris rarus* (Ye & Fu), 2-

3 cm in length, were acclimated for one week before testing in aquaria (15 cm diameter and 12 cm height). To test the efficacy of spraying, 3-5 cm thick turves collected from the Nanhu river bank in Wuhan city were placed in porcelain enamel trays (35 cm × 45 cm x 1575 cm).

NN powder was made up in dechlorinated tap water to the following concentrations:- 0.025 0.05 0.1 0.2 0.4 0.8 1.6 3.2 mg/litre. Parallel tests were done to compare NN with NS and NCL. For aquatic toxicity tests, 30 active, mature *O. hupensis* (3.5 to 7.5 mm in length) were exposed for 24, 48 and 72 h in 2 litres of test solution. The snails were then rinsed in dechlorinated tap water and kept for a 24h recovery period, after which mortality was assessed using WHO (1993) criteria and probability analysis.

For spray tests, NS and NCL powders were combined in the following ratios 1:1, 1:2 and 1:4. Thus dosages were calculated to represent the concentrations:- NS:NCL 0.2:0.2 g/m^2; NS:NCL 0.1:0.2 g/m^2; NS:NCL 0.1:0.4 g/m^2. This NN was then sprayed into porcelain enamel trays and 300 snails were put in each tray. 50 snails were sampled each day to assess mortality using WHO (1993) criteria.

For aquatic tests of molluscicidal toxicity, groups of 30 snails were each immersed for 24h in the following concentrations of the test materials:- 0.2, 0.4, 0.8 1.6, 3.2 mg/litre. For fish toxicity tests, ten fish were tested for 24 h at each of the following concentrations:- 0.025, 0.05, 0.1, 0.2, 0.4, 0.8, 1.6, 3.2 mg/litre.

Field tests were also undertaken. For immersion tests in the field, three ponds (length 3 m, width 3 m) were selected. Using the 1:1, 1:2 and 1:4 ratios and concentrations described above, snails were exposed to test solutions for 24, 48 and 72 hours. After exposure, snails were collected, rinsed and mortality assessed as before. Field tests of spray application were undertaken on the river bank at Fushui. Three sites of 100 m^2 were sprayed using the previously described 1:1, 1:2 and 1:4 ratios, concentrations and test times. Field temperatures were 8-19 °C.

RESULTS

Immersion tests in the lab and the field

48 h exposure to 0.4 mg/litre NN at 23-25 °C gave 100 % mortality compared with 93.3 % and 6.7 % for NS and NCL respectively. The LC_{50} for NCL and NN was 0.0976 mg/litre and 0.0466 mg/litre respectively. The ratio of increased effect (SR) was 2.09 and the common toxin coefficient (CTC) was 172 (Dai, *et al.* 1997a & b). In the field, the use of 0.2 mg/litre of NN for 48h and 72 h at 8-19 °C caused snail mortalities of 97 % and 100 % respectively (Table 1).

Spray tests in the lab and the field

Snails were exposed to 0.4 g/m^2 of NN for 48h at 19 °C. There was a mortality of 100 % in the lab and 81.1 % in the field (Table 2).

Table 1. Per cent mortality caused by different chemicals and dosages in the laboratory (room temperature 23-25 °C water temperature 21-23 °C)

	NS			NCL			NN		
mg/litre	24 h	48 h	72 h	24 h	48 h	72 h	24 h	48 h	72 h
3.2	63.3	100	100	56.7	100	100	100	100	100
1.6	56.7	100	100	46.7	100	100	100	100	100
0.8	43.3	100	100	43.3	96.7	100	100	100	100
0.4	43.3	96.7	100	37.9	70	96.7	100	100	100
0.2	33.3	93.3	96.7	23.3	66.7	96.7	93.3	100	100
0.1	16.7	43.3	93.3	16.7	43.3	93.3	20.7	93.3	100
0.05	6.7	36.7	66.7	6.7	37.9	66.7	0	46.7	20
0.025	0	20.7	26.7	0	20.7	26.7	0	10	3.3
Control	0	3.3	3.3	0	3.3	3.6	0	3.3	3.3

Table 2. Molluscicidal effect of spray experiments in lab. and field (lab. temp. air 23-25 °C, water 21-23 °C; field temps. air 8-19 °C, water 6-17 °C).

		24 h		48 h		72 h	
Test site	Dosage (g/m^2)	No.of snails	Mortality (%)	No.of snails	Mortality (%)	No.of snails	Mortality (%)
Lab	1:1	50	96.0	50	100	50	100
	1:2	50	94.0	50	100	50	100
	1:4	50	88.0	50	96.0	50	98.0
	Control	50	0.0	50	0.0	50	0.0
Field	1:1	142	54.9	111	81.1	61	83.6
	1:2	109	30.3	107	60.7	81	71.6
	Control	175	1.1	114	2.6	109	3.7

Water leaving by snails

At a concentration of 0.2 mg/litre, the rate of water leaving was 96.7 % for NS, 56.7 % for NCL and 27 % for NN. Thus the rate of water leaving was 72.1 % lower for NN than for NS ($chi^2 = 138.39$, $P<0.01$, Table 3).

Toxicity tests on fish

All fish survived 24 h immersion in NS. At 0.2 mg/litre, fish mortality rates were 40 % for NS and 20 % for NN (Table 4).

Comparison of costs

The amount of molluscicide needed to treat 10000 m^2 of snail-affected area at current prices was calculated. NN was 77.6 % cheaper than NCL. For a particular volume of molluscicide, the area of snail control afforded by NN was five times that afforded via NCL (Tables 5 and 6).

DISCUSSION

Both NS and NCL are commercially available molluscicides. After mixing them as NN, they became more effective when used via immersion (0.4 mg/litre) and spraying (0.4 g/m^2). For example, NN had 50 % lower fish toxicity than NS alone and caused 72 % lower water-leaving activity than NCL. For a treatment of 10000 m^2, NN was 77.6 % cheaper than NCL. In addition, the ratio of increased effect (SR) was 2.09 and the common toxin coefficient (CTC) was 172. It thus appears that NN could be a more effective molluscicide than NS or NCL used separately.

Water development projects can increase problems of schistosomiasis (Xu & Dussart, 2001). In China, the problem is made worse by the association between water buffalo and humans, where the former act as a reservoir host in the life cycle of *Schistosoma japonicum* Katsurada 1904. Humans can be protected by education and treatment with drugs such a praziquantal. However, if the schistosomiasis cycle continues through water buffalo, then human reinfection is assured. Snail control is, therefore, an essential part of integrated pest management.

By increasing the treatment areas at reduced cost, NN could help to protect both humans and reservoir hosts such as water buffalo, and thereby accelerate social and economic development in areas which are endemic for schistosomiasis in China. NN has now been patented but further research is needed to evaluate its environmental safety and stability, and more chronic and sub-chronic toxicity tests are needed.

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Table 3. Results if water leaving experiments (air 23-25 °C, water 21-23 °C)

Dosage (%)	Proportion of snails leaving water %		
	NS	NCL	NN
3.2	96.7	36.7	0
1.6	96.7	36.7	6.7
0.8	96.7	40.0	20.0
0.4	96.7	46.7	23.0
0.2	96.7	56.7	27.0
0.1	100	70.0	47.6
0.05	100	70.0	60.0
0.025	100	73.3	66.6
Control	96.7	96.7	96.7

Table 4. Result of acute toxicity test to fish at an air temperature 23-25 °C and water temperature of 21-23 °C

Dosage (mg/litre)	No.of fish	Mortality (%)		
		NS	NCL	NN
3.2	10	0	100	100
1.6	10	0	100	100
0.8	10	0	100	100
0.4	10	0	100	100
0.2	10	0	40	20
0.1	10	0	0	0
0.05	10	0	0	0
0.025	10	0	0	0
Control	10	0	0	0

Table 5. Cost calculation for the three molluscicides

	Unit cost (Ton/10000Yuan)	Cost per gram(Yuan/g)	Recommended dosage g/m^2	Cost for snail control Yuan/ha	Cost reduction compared NN with NCL	Cost reduction compared NN with NS
NS	4.0	0.040	0.4	320	77.6 %.	7.5 %
NCL	3.3	0.033	2.0	1320		
NN	3.7	0.037	0.4	296		

Table 6. Comparison of snail control area using the three treatments

	Amount applied kg	Application rate g/m^2	Area of snail control ha
NS	100	0.8	12.5
NCL	100	4	2.5
NN	100	0.8	12.5

A new technique for preventing the spread of *Oncomelania hupensis* Gredler snails in irrigation systems in China

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ABSTRACT

To investigate possibilities for controlling the spread of *Oncomelania hupensis* in irrigation schemes in China, hydromechanical and biological studies were combined with field observations. Factors measured included sedimentation rate of snails (max. size 3mm) and eggs and specific gravity of both snail and snail eggs. Five practical formulae were developed to describe the dropping speed of snails in both running and still water. When sedimentation was combined with abstraction of irrigation water from the middle of the water column, 100% prevention of spread was possible.

INTRODUCTION

The amphibious prosobranch snail *Oncomelania hupensis* Gredler is an intermediate host of schistosomiasis in South East Asia where the parasite infects both water buffalo and humans. It spreads through irrigation systems in endemic areas of China (WHO, 1993), and the problem is serious in areas such as the middle reaches of the Yangtze River. Floodgates (sluices) are used to lead irrigation water away from the main river but this can spread snails through the canal system. The endemic area then enlarges, threatening livestock and people (Xu & Fang, 1988; Xu, *et al.*,1989). The aim of the work reported here was to investigate the distribution of *O.hupensis* in irrigation systems and to develop and test systems for snail control by engineering.

MATERIALS AND METHODS

Field surveys of snail distribution were carried out within 2 km of floodgates on major rivers in endemic areas. Both systematic and random sampling were used to survey snail densities. For the former, a hectare was regularly divided into 200 m^2 cells and a 0.1 m^2 quadrat was used to randomly sample within each cell. To investigate the effect of sluices, data concerning irrigation and drainage were collected from local water conservation departments. The specific gravities of adult snails and eggs were measured (Xu, *et al.*,1997; Xu, *et al.*, 2000a).

The dropping speed of snails in still water was measured in a 1m glass tube (Yang, *et al.*,1992). To test the dropping speed of snails in running water, a glass trough was used (length 3600 cm, width 60 cm, depth 90 cm). Water was supplied at 104 litres/s and a maximum velocity of 107 cm/s. A range of water velocities was used and formulae for dropping speed were derived

(Zhang, *et al.*, 1994). Snail motion in running water was also monitored (Yang, *et al.*, 1994). Based on these observations, engineering management strategies of (a) snail settlement using pools and (b) abstraction of water from the middle level of a water body were implemented in endemic areas. The success of these processes was monitored (Yang, *et al.*, 1995) and health economic data were used to evaluate their cost effectiveness.

RESULTS

Distribution of *O.hupensis* on both sides of the floodgates

381sluices (floodgates) are distributed along the dikes of 14 major rivers in Hubei province. Thus water is guided by dykes from the river to the floodplain to the cultivated inland area which is inside embankments. These sluices were classified according to the snail habitats within 2 km^2. It was presumed that sluices with snails on both sides had been responsible for introducing snails from the floodplain side to the inland side.

155 sluices (40.7%) were snail-free on both sides. 226 sluices (59.3%) had snails on one or both sides. Of these 226 sluices, 11.1% were snail-ridden on the inland side, 50.4% were snail-ridden on the floodplain and 38.5% were snail-ridden on both the floodplain and inland areas. Of 87 sluices, 57.5% on the eight main rivers appeared to have spread *O. hupensis* into irrigation canals. The Dongting Lake area in the middle reaches of the Yangtze River in Hunan province had 665 floodgates, distributed on the dikes of 16 major rivers. 13 sluices were abandoned and 114 sluices had a drainage function only. 538 sluices were used for irrigation, of which 443 (82.3%) were snail-ridden. Of these sluices, 35.1% were snail-ridden on both the floodplain and inland areas, 46.1% were snail-ridden on the floodplain side and 1.1% were snail-ridden on the inland area side.

A field survey of snails spread by floodgate irrigation was carried out at Shuan-Yi gate on the Jiang-Han Plain. During the flood season of June and September of 1996, snail density ranged from 0.63-1.77 snails/0.1m^2 on the mud surface of the floodplain after the gate was opened for irrigation. On a typical occasion, 125 snails (including 98 juveniles), were netted in a standardised procedure using a 0.1m^2 scoop net where water entered the gate.

A survey of 5 floodgates in the Dongting Lake area during the flood season of August 1996 showed snail densities of 0.3-9.2 snails/m^2 on the mud surface of the floodplain after the gate was opened for irrigation. In a typical scoop net survey, 38 snails (including 26 juveniles) were found in 120 scoops where water entered the gates. A field survey of the snails which had spread from canals and ditches into inland areas was undertaken. A 693.3 ha snail area was distributed on three main canals. 292 branch canals were connected with three main canals. 189 of these branch canals (64.7%) were snail-ridden, the associated area being 877.3 ha.

Specific gravity of snails and snail eggs

The specific gravity of live snails ranged from 1.75 -1.84 g/cm^3 with an average of 1.8 ± 0.01 g/cm^3. The specific gravity of snail eggs ranged from 2.25-2.33 g/cm^3 with an average of 2.29 ± 0.01 g/cm^3.

Dropping speed of snails in still water

Dropping-speed formulae for both snail eggs and juvenile and mature snails were derived from Newton's law of inertia using the following abbreviations :-

D	Diameter of the snail shell (mm).
H	Height of the snail shell (mm)
G	Acceleration due to gravity (cm/s^2)
γ_e	Specific gravity of the snail egg (g/cm^3)
γ_s	Specific gravity of the snail (g/cm^3)
γ_w	Specific gravity of water ($\approx$1g/cm^3)
W_l	~~Dropping speed of the snail in stable water (cm/s)~~
W_e	Dropping speed of a snail egg in stable water (cm/s)
W_f	Dropping speed of the snail in flowing water (cm/s)
K	Synthetic index of snail starting movement
m	Distribution index of flow
L	Snail dropping distance in flowing water (cm)
U	Average water velocity (cm/s)
C_b	Coefficient of water resistance
n	Index of power
H	Depth of water
v	Dynamic viscosity of fluid (cm^2/s)

Dropping speed formula for small snails in still water

$$W_1 = \pi/ 480v * D^{2.5}/ h^{0.5} (\gamma_s\text{-}\gamma_w/\gamma_w)g$$

Dropping speed formula for medium sized snails in still water

$$W_2 = \sqrt{\pi D^2/ 2.4\ h\ (\gamma_s\text{-}\gamma_w/\gamma_w)\ g}$$

Dropping speed formula for large snails in still water

$$W_3 = \sqrt{\pi D^2/ 3h\ (\gamma_s\text{-}\gamma_w/\gamma_w)\ g}$$

Dropping speed formula for snail eggs in still water

$$W_e = \sqrt{4/3\ C_a\ (\gamma_e\text{-}\gamma_w/\gamma_w)\ g\ D}$$

The formula for dropping speed of snails in flowing water was derived by including the starting velocity of the snail into the equation:-

$$W_m = 4\ \sqrt{U^4 +1/2\ C_b{}^2\ \pi^2/g^* D^2/ 3\ (\gamma_s\text{-}\gamma_w/\gamma_w)^2\ g^2}$$

where the starting velocity formula for the snail in flowing water is:

$$Uo = K\sqrt{D^2/ h(\gamma_s\text{-}\gamma_w/\gamma_w)g(H/D)^m}$$

To validate these formulae, 156 snails were used to predict theoretical dropping speeds in still and flowing water. There was no statistically significant difference between the real and predicted results ($t = 0.4$, $P>0.05$). Based on the above results, a formula for dropping distance was obtained:-

$$L = m(uH/W_o)^n$$

Characteristics of snail movement in flowing water

Studies on the movement of *O. hupensis* showed that snails dropped in a level posture, without rotation, pitch or yaw. At a water velocity <10 cm/s, snails dropped to the bottom of the trough and did not move. As the velocity exceeded 10 cm/s, snails rolled along the bottom of the trough at a rate which was directly proportional to the water velocity. At <10 cm/s water velocity, the track of movement of a dropping snail in moving water from the surface to the bottom was perpendicular to the surface. At velocities >10 cm/s, the track formed a parabola. As snails dropped in the experimental channel, lateral movement was restricted to within 5 cm of the central dropping line. At a water velocity of 20 cm/s, 52% of the snails crawled against the current. At >20 cm/s, snails only crawled downstream, or laterally.

Operational research in the field

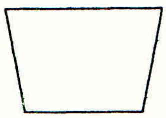
Figure 1. Echelon section

On the basis of the results described above, it was decided to use sedimentation in pools to prevent the spread of snail populations. The use of pools could also allow the focused use of molluscicide. Experimental pools were built behind the floodgate, on the side away from the river.
Key design factors for a pool were (i) current speed in the pool (ii) depth (iii) width (iv) length. It was clear that the maximum velocity of flow should be less than 20 cm/s. Cross sectional area (A) was determined by discharge through the floodgate (R), and maximum velocity of flow through the floodgate (V). Thus A =R/V. The cross sectional shape was an echelon (Figure 1). The ratio of width to depth was based on local conditions and the length was designed to be at least twice the dropping distance.

Since field surveys had shown *O.hupensis* to be distributed both on the surface and at the bottom of the water column, a principle of water abstraction from the middle level of the water column in the river was applied. Thus the take-off pipe should form a trumpet- shaped opening so that no whirlpool would form, and should be 3-5 metres below the depth of low-water flow in the river. A constant take-off depth was maintained by means of a floating pontoon.

Assessment of efficacy of the engineering approaches

Sedimentation pools were set up at the Wangtai floodgate in Yingchen County. A field survey showed that inside the embankment, the original snail-affected area of 0.37 million m^2 was reduced to zero, as was the number of snail habitats. A system for abstraction from the middle level of a water body was set up at Shuanyi floodgate in Jiayu County. Field surveys showed that the snail areas were reducing three years later. Although many snails were found on the floodplain side, no snails were found in the canal leading water inland from the floodgate in 1995.

Analysis of cost effectiveness

Methods from health economics were used to analyse cost-effectiveness (Xu, *et al.*, 2000b). For example, inputs included engineering costs and management costs; outputs included reduction of morbidity, reduction in snail control costs, reduction of protection costs, increase in agricultural yield etc. Using data for 1992, the ratio of cost and benefit was 1: 274. Clearly, these preventative measures could give great benefit for a relatively small investment.

DISCUSSION

The spread of intermediate hosts of schistosomiasis through water systems has been well-studied (eg. Xu, *et al.*, 1993; Bolton, 1988; Xu & Dussart, 2001). However, there has been little recent, systematic research based on achieving snail control through engineering principles. The work described here began with the observation that snails might be spread by floodgates which lead water from the floodplain into canals inside the embankment. On this basis, research was undertaken to clarify the movement characteristics of snails dropping through the water column.

Specific gravity and shape geometry are important factors for sedimentation of snails. Shape geometry is particularly important in relation to size, due to allometry of the shell during the ontogeny of *O. hupensis*. Allometry directly influences the resistance coefficient of a dropping snail. Thus, three snail sizes were investigated and appropriate model equations were developed both for still and running water. The equations were validated by using replicated observations to compare real and predicted values. These results form the basis of a new approach to snail control.

Under varying conditions of water depth and velocity of flow, dropping time, state, track, distance and movement characteristics were all important parameters in the development of a management practices. These were tested by field engineering. Based on the characteristics of the water, the snails and the model equations, two particular management practices were proposed and tested. These comprised firstly, the use of sedimentation pools and secondly, abstraction from the middle levels of the water column. These were tested at specific localities for several years and appeared to make a significant, cost effective contribution to snail control. Currently, these techniques are being applied in endemic areas of schistosomiasis in China including projects such as the "World Bank Loan Project for Dike Strengthening on the Yangtze River in China" and the "Water Resources Translation from Southern to Northern China". It is expected that these practices will bring social and economic benefits to China.

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