FACTORS AFFECTING GREAT BLUE HERON REPRODUCTION IN SOUTHCENTRAL WASHINGTON

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ABSTRACT

I estimated fledging success, factors affecting fledging success (colony size, nest eggshell thickness, incubation initiation, brood size, hatch order and forage distance), and eggshell thickness at five Great Blue Heron (*Ardea herodias*) colonies along the Columbia River, adjacent to the Hanford Site, Washington, from March 1995 through August 1996. Of 190 nestlings from 66 nests observed, 175 (89 marked and 86 unmarked) survived to fledging.

I found no difference in fledging success between years ($F = .0133$, 1 df, $P = .9085$) or between marked and unmarked nests ($F = .1716$, 1 df, $P = .68$), however, I did find the proportion fledged in 1996 (0.95) was significantly higher than 1995 (0.78) ($F = 11.4537$, 1 df, $P = 0.0012$).

I found the number of nestling Great Blue Herons fledged per nest along the Hanford Site to be higher for early nesting herons ($F = 23.2749$, 1 df, $P < 0.0001$) and nests with larger broods ($F = 59.9539$, 1 df, $P < 0.0001$). I also found individual fledging success to be higher for older nestlings ($\chi^2 = 7.1351$, 3 df, $P = 0.0677$). No relationship was found for nest eggshell thickness ($F = 2.0385$, 1 df, $P = .1738$), colony size ($F = .9363$, 1 df, $P = .3655$) or mean adult foraging distance ($F = .5503$, 1 df, $P = .4625$) when compared to fledging success in this study.

Mean eggshell thickness was estimated for each of five colonies using 57 eggshells collected from 22 known nests in 1996: and was significantly different among colonies ($F = 3.4431$, 4 df, $P < .05$). Mean eggshell thickness of four colonies using 143 eggshells collected from unknown nests in 1995 and 1996, again was significantly different ($F = 5.5609$, 3 df, $P = .001$).

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GENERAL INTRODUCTION

Approximately 80 kilometers (km) of Columbia River flows through the United States (U.S.) Department of Energy's (DOE) Hanford Site in southcentral Washington. This is the only remaining section of Columbia River not directly impounded by a hydroelectric dam (Rickard and Gray 1995). This segment, known as the "Hanford Reach", provides habitat for spawning Chinook Salmon (*Oncorhynchus tshawytscha*), island nesting Canada Geese (*Branta canadensis*), and wintering Bald Eagles (*Haliaeetus leucocephalus*) (Geist 1995). Over the past 40 years these important fish and wildlife populations have been monitored annually as part of the Hanford Sites' environmental monitoring programs (Woodruff and Hanf: 1992 111-115pp). In the early years of monitoring, these populations were much lower than they are today and this is attributed to the absence of impoundments along the Hanford Reach which elsewhere along the river have covered historic spawning beds, and nesting islands with slack water and eliminated salmon carcasses as foods for eagles (Rickard and Gray 1995). Historically Great Blue Herons (*Ardea herodias*) have nested in trees at abandoned farm house locations close to the river shore but nest counts and reproductive success have not been systematically monitored. This is due in part to the difficulty of obtaining accurate clutch size and fledging success counts for tree nesting herons and because herons are not federally listed as a threatened or endangered species. Also, herons are not eaten as food by people thereby eliminating the food chain pathway of chemical contamination to people, which is a major objective of environmental surveillance at Hanford.

Although herons are not in the food chain that leads to people, they have been used as indicators of the availability of gamma-emitting radionuclides (Rickard et al. 1978), metals, lead, mercury, and cadmium (Fitzner et al. 1982), and organochlorine residues, DDE and PCBs (Fitzner et al. 1988) on Hanford. The

concentrations of these materials in heron feces, eggs and body tissues were too low to expect interference with reproductive success. Reproductive success estimates were determined in 1981-1982, when only one active heron colony occurred along the Hanford Reach, and showed that herons had a high rate of productivity, two young per nest (Blus et al. 1980, 1985).

Eggshell thickness was also measured at this colony, but the total number of eggs was only 13. The mean eggshell thickness of 0.360 millimeters (mm) was 0.029 mm less than the mean value obtained for 64 museum specimens collected throughout the Pacific Northwest in the years prior to 1947, yet above values known to reproductive problems (Fitzner et al. 1988).

A wide variety of industrial contaminants are present in the soil, sediment, ground water, and in Columbia River water near Richland, Washington (Napier et al. 1995). While only some of these contaminants including organochlorines, dioxins, and some heavy metals accumulate through the food chain to detrimental levels, others are of public interest and continue to be monitored by Hanford environmental surveillance. River contaminants originate from Hanford Site facilities (Table 1) as well as upriver sources (Table 2), which are transported by the river (Fig. 1). Concentrations of radionuclides have been decreasing since the conclusion of weapons production on Hanford, in the early 1970's (Cushing et al. 1981; Eberhardt et al. 1989). Currently river bottom sediments have only trace quantities of radionuclides (Rickard and Gray 1995), and the river is environmentally designated as "Class A" (Excellent) (Dirkes and Hanf 1995).

Even though the Columbia River water is within safe limits for drinking, long-term monitoring of Columbia River wildlife populations is needed because of the potential for bioaccumulation of toxic materials (Stober and Nakatani 1992; Rickard and Gray 1995), such as organochlorines, certain dioxins, and some heavy metals. Because these contaminants can accumulate in fish tissues (Bache et al. 1971;

Table 1. List of identified contaminants of concern from the Hanford Site, Washington.[a]

In Columbia River, Groundwater,[b] Sediment, and Soil		
Antimony	Cobalt-60/particles	Mercury
Arochlor 1248 (PCB)	Copper	Nitrate/nitrite
Arsenic	Diesel Fuel	Phosphate
Cesium-134	Europium-152	Silver Chloride
Cesium-137	Europium-154	Strontium-90
Chlordane	Lead	Zinc
Chromium	Manganese	

[a] Information from Napier et al. 1995.
[b] Hanford groundwater within 150 meters (500 feet) of the Columbia River.

Table 2. Contaminant sources entering the Columbia River, upriver from Richland, Washington.

Location	Source	Contaminant	Reference
Canada	lead-zinc smelter, pulp mill, and fertilizer complex.	Heavy Metals, dioxins, and furans	Smith 1987; Johnson et al. 1990; Serder 1993; Serdar et al. 1994.
Northern Idaho	Mining	Heavy Metals	Johnson et al. 1990
Washington			
Central	agro-chemicals	DDT and metabolites	Hopkins et al. 1985
Hanford	nuclear reactors	Radionuclides	Department of Energy 1997

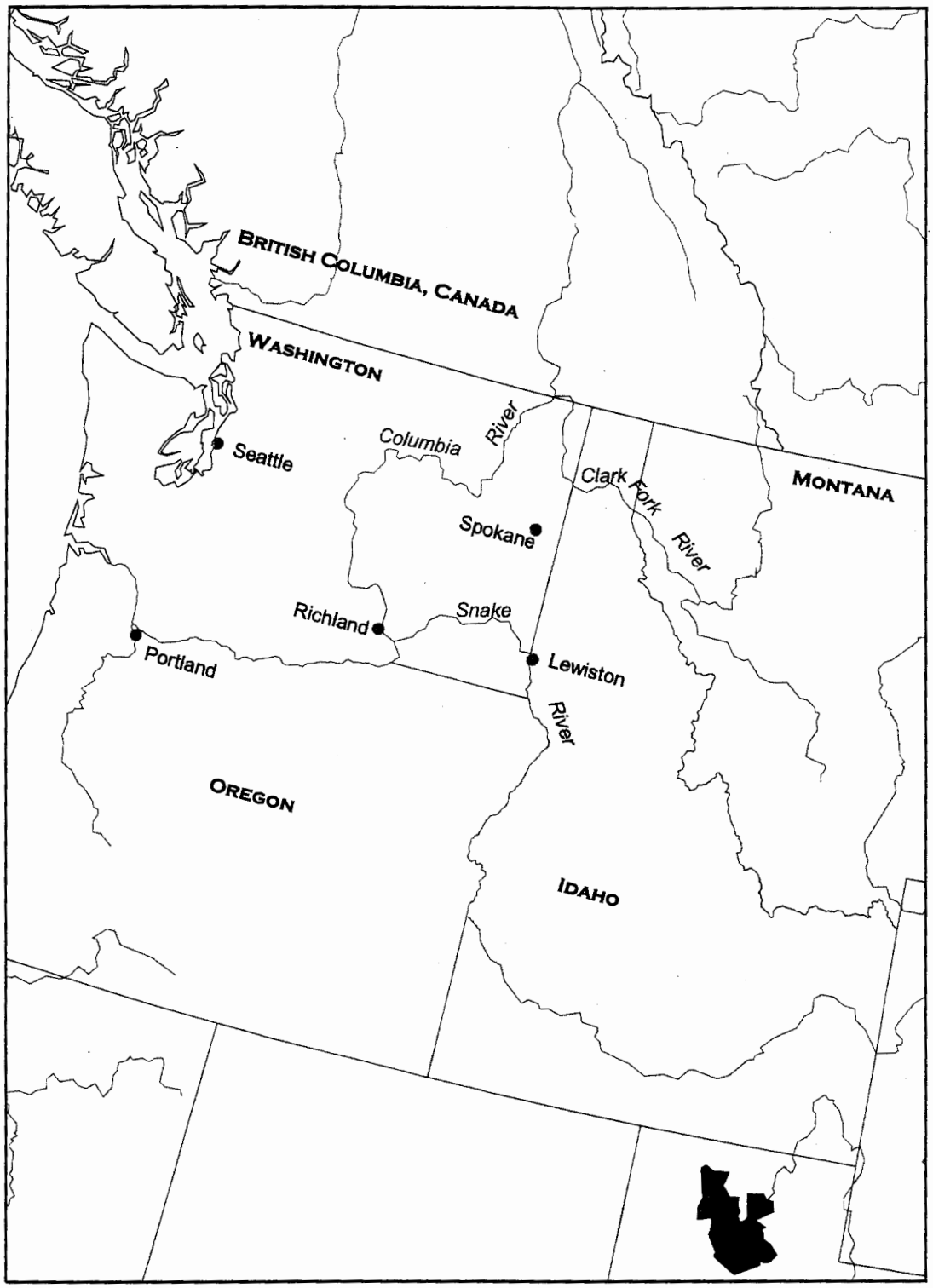

Figure 1. Columbia River drainage basin

Scott 1974; Gahler et al. 1982; Lech and Peterson 1983; Malins et al. 1984), and be transferred to fish-eating birds (Burger and Gochfeld 1993), predicting toxic chemical impacts in avian piscivores from water, sediment, and invertebrate samples is often inaccurate (Goede 1985).

Currently there are no vertebrate piscivores being used as biological monitors at Hanford. Great Blue Herons would be useful for monitoring different stretches of the Columbia River, because as many as nine breeding colonies are distributed along the Hanford Reach. However, in addition to contaminant sampling, estimates of reproductive success and eggshell thickness measurements are also needed at these colonies.

The goal of this study was to estimate the reproductive success at several Great Blue Heron colonies along the section of the Columbia River that flows through the Hanford Site, along with providing valuable baseline data for future studies. In Chapter 1, Great Blue Heron breeding biology and factors known to affect their, and related species, reproductive success is reviewed. Chapter 2 describes reproductive success of Great Blue Herons and explores some factors affecting their productivity on the Hanford Site, as well as assessing the usefulness of measuring eggshell thickness as an indicator of population health.

CHAPTER 1

LITERATURE REVIEW

GREAT BLUE HERONS

Reproductive success in Ardeids and other fish-eating birds have been the focus of numerous studies (Pratt 1970, 1972; Henny and Bethers 1971; Faber et al. 1972; Henny 1972; Collazo 1979,1981; Quinney 1982, 1983; Custer et al. 1983; Forbes et al. 1985; Pratt and Winkler 1985; Butler 1993, 1995). The purpose of this chapter was to review the literature on Great Blue Herons, focusing on breeding biology and factors affecting their reproduction.

Great Blue Herons are North America's largest and most widely distributed Ardeid (Palmer 1962). They are colonial nesters, with the same colonies occupied year after year (Custer and Osborn 1977; Erwin 1978; Custer et al. 1980), and the number of active nests within a colony being predictable from one year to the next (Custer et al. 1980). Heron colonies are usually established in tall trees near local foraging habitat (Bent 1926; Gibbs 1991; Butler 1995), with distance between colonies and colony size largely determined by food supply (Gibbs et al. 1987; Butler 1995).

Herons are monogamous for the nesting season (Bent 1926; Mock 1979), but lack nest site fidelity and mate fidelity between years and are willing to occupy different colonies between breeding seasons (Simpson 1984; Simpson et al. 1987). Males return first to the colony to choose a nest site from which they advertise for a mate (Mock 1976). Individual nest placement within a colony may influence the success of nesting herons. For example, Simpson et al. (1987) found the most successful nests were closer to the center of the colony than unsuccessful nests. This difference was largely attributed to predation because the outermost nests were more accessible to predators. Large colonies also have lower rates of predation

(Patterson 1965; Robertson 1973) and higher reproductive success (Forbes et al. 1985; Thomas 1986) than smaller colonies. This suggests that the interior nesters may be buffered by the perimeter nesting herons.

Herons diet consists mainly of fish (72%) (Palmer 1962), but they also feed on other aquatic organisms, reptiles, small mammals, birds, and insects (Bent 1926; Jewett et al. 1953). There have been many studies on heron foraging site selection and how they forage. Krebs (1974) and DesGranges (1978) suggested that herons of the same colony foraged in similar areas, whereas the more recent findings by Simpson et al. (1987) state that neither members of a pair nor herons nesting in the same sector of the colony fed in the same area. Kushlan (1978) indicated that Great Blue Herons tend to forage non-territorially in concentrated food patches, and defend a large territory when food supplies are widely dispersed. This may explain why several studies indicated herons forage territorially (Nicholson 1929; Owen 1955; Bateman 1970; Peifer 1979), while others found herons foraging non-territorially (Dowd and Flake 1985; Butler 1994).

Although some herons travel > 35 km to feed (Marion 1989), most forage within a few km of their colony (Kushlan 1978; Marion 1989; Gibbs 1991). It has also been shown that use of a wetland by foraging adult herons decreases as the distance between the colony and wetland increases (Custer and Osborn 1978; Thompson 1979; Benoit et al. 1993), and those adults feeding nearest the colony, bred more successfully (Simpson et al. 1987). Other factors affecting foraging success and habitats selected by herons were tidal depth (Custer and Osborn 1978; Bayer 1981), wind, and cloud cover (Bovino and Burtt 1979). Additional factors affecting foraging location in a riverine system were date, wind direction, and water level (Benoit et al. 1993).

Great Blue Herons are able to breed after their second winter (two years old) (Bent 1926). They typically have only one brood, but if the initial clutch is destroyed

they may renest (Miller 1944). Laying dates for eggs can be determined by egg color (± 1 day) (Custer 1991). Egg laying in Western Oregon begins in early March, but may differ in other parts of the United States and Canada (Henny and Bethers 1971). Average clutch size is four eggs (Bent 1926; Jewett et al. 1953), which they incubate for 26-27 days (Vermeer 1969). Between 74 and 84% of all eggs that are laid successfully hatch for several North American heronries (Pratt 1970; Quinney 1983). Henny (1972) postulated that recruitment was greater in northern colonies to compensate for higher mortality. He also estimated that 1.91 young per breeding pair of northern U.S. herons, must be fledged to maintain a stable population.

In general, herons with larger clutch sizes (Henny and Bethers 1971; Tomlinson 1975; Rodgers 1980; Tremblay and Ellison 1980; Pratt and Winkler 1985), and those that nest early in the breeding season (Pratt and Winkler 1985; Butler 1995) have a higher fledging rate. Reduced fledging success may be due to smaller clutches that typically occur later in the nesting season, possibly the result of replacement clutches (Jenni 1969; Wolford and Boag 1971; Batt and Prince 1979; Butler 1995) or younger breeding birds (Lack 1968; Johnsgard 1973; Ryder 1980;).

Eggs hatch in the same order as they were laid (Custer and Frederick 1990). This occurs because incubation typically begins after the first egg is laid and asynchronous egg laying produces one to two day intervals in hatching (Lack 1968; Pratt 1970; Quinney 1982; Mock 1985; Custer et al. 1992). Relative size of the final egg laid in a clutch is generally smaller than other eggs (Slagsvold et al. 1984; Custer and Frederick 1990).

Nestlings are altricial and are fed by both parents for some period of time after hatching. Young are constantly watched by adults until they are about 21 days old (Pratt 1970; Butler 1993), at this time chicks can walk firmly across the nest and are left alone by foraging adults (Pratt 1970). Sullivan (1988) indicated adults with large broods required more foraging trips to feed young than those with smaller

ones. Young herons one week old to first flight averaged four feedings a day, during daylight hours (Pratt 1970). Herons will forage at night (Millstein et al. 1970; Dennis 1971; Krebs 1974), but only half as much as during the day (McNeil et al. 1993). Nestlings are completely dependent on parental feedings prior to fledging, even though they are very mobile at least three weeks before they actually fledge (Frederick et al. 1993). Late hatching nestlings fledged sooner than chicks that hatched earlier (Pratt 1970; Butler 1995). Average age of nestling herons, at first flight, is 52.6 days (Vermeer 1969), and dispersal movements are in all directions (Dusi 1967; Henny 1972).

Young herons have low survival rates following hatching. For example, Miller (1944) suggested that nestling mortality in excess of 40% occurs, and Henny (1972) reported a mortality of 69% for first year herons, with 29% annual mortality after that. Butler (1994) also reported low survival of first year herons due to poor winter foraging. Nestling age with the highest rates of mortality varied between one and six weeks (Pratt 1970; Gill 1973; Collazo 1979, 1981; Pratt and Winkler 1985). The leading cause of chick mortality has been attributed to starvation of the smaller younger chicks which are unable to compete for food with older siblings (Pratt 1972; Collazo 1981; Quinney 1983; Mock 1985; Sullivan and Payne 1988) and from falls from the nest, unrelated to starvation (Butler 1995). Because the smallest nestling is invariably the first one to die, a dominant, size hierarchy exists in the nest (Mock 1985; David and Berrill 1987). Most aggressive interactions occur in nests containing three or four nestlings. Less competition probably exists at nests with two young thus leading to fewer cases of aggression (Sullivan and Payne 1988). While food resources are sufficient for the entire brood to survive, sibling rivalry may be a direct cause of mortality (Mock 1984; Mock and Parker 1986; Sullivan and Payne 1988). Other factors influencing nesting success include human disturbances

(Simpson et al. 1987), heavy rain storms (Kelly et al. 1993), and fire (Rickard pers. comm.).

Although predation has a minor effect on heron reproductive success (Lopinot 1951; Bayer 1979; Kelsall and Simpson 1980), it may result in selection for colonial breeding in herons. Heavy predation pressure is suspected as one cause of the frequent relocation of Great Blue Heron colonies (Simpson 1984; Simpson et al. 1987). Butler (1995) suggested that relocation was more likely to occur after adults were killed than if chicks are taken. Predators of Great Blue Heron adults, chicks, or eggs include Common Crow (*Corvus brachyrhynchos*), Common Raven (*Corvus corvax*), Bald Eagle, Raccoon (*Procyon lotor*) (McAloney 1973; Simpson and Kelsall 1979; Quinney 1983; Simpson et al. 1987), North-western Crow (*Corvus caurinus*) (Butler 1989), and Great Horned Owl (*Bubo virgiinianus*) (Pratt and Winkler 1985).

Contaminants also affect avian piscivores. Fish-eating birds have been identified as the most likely trophic level to become contaminated (Peterson 1969). For instance, Burger and Gochfeld (1993) found that several metals were highest in nestling Great Egrets (*Egretta alba*). They postulated that unlike smaller ardeids, larger Great Egrets bioaccumulate higher concentrations of metals because of their preference for large fish. Great Blue Heron nestlings would also be expected to have a similar potential for bioaccumulating high levels of these metals, because like Great Egrets, Great Blue Herons are one of the top avian predators in an aquatic food chain (Thompson et al. 1992).

The four general groups of environmental contaminants known to affect colonial waterbirds are petroleum, metals, organochlorine compounds, and organophosphorus pesticides (Parnell et al. 1988) including such contaminants as mercury (Connors et al. 1975; Gochfeld 1975; Koeman et al. 1975; Heinz 1976; Finley and Stendell 1978; van der Molen et al. 1982), lead (Kendall and Scanlon 1981; Kendall et al. 1982; Burger and Gochfeld 1985, 1988; Burger 1990), fluoride

(Hoffman et al. 1985; Pattee et al. 1988), selenium (Hoffman and Heinz 1988; Skorupa and Ohlendorf 1991), halogenated aromatic hydrocarbons (Fitzner et al. 1988; Moul et al. 1989; Bellward et al. 1990; Gilbertson et al. 1991; Hart et al. 1991; Nosek et al. 1992; Sanderson et al. 1994a, b), and DDE (Fitzner et al. 1988; Ohlendorf and Marois 1990; Custer et al. 1997).

My review indicated a wide variety of factors can potentially affect productivity in Great Blue Herons and other fish-eating birds. Almost all areas of heron breeding biology were identified as affecting their reproduction, such as: nest placement (Simpson et al. 1987), nest initiation (Pratt and Winkler 1985; Butler 1995), clutch size (Henny and Bethers 1971; Tomlinson 1975; Rodgers 1980; Tremblay and Ellison 1980; Pratt and Winkler 1985), colony size (Forbes et al. 1985; Thomas 1986), and foraging distance from the colony (Simpson et al. 1987). Other equally important nonbreeding factors were also shown to affect avian piscivore reproduction, including human disturbance (Simpson et al. 1987), heavy rain storms (Kelly et al. 1993), and contamination (Skorupa and Ohlendorf 1991; Sanderson et al. 1994a, b; Custer et al. 1997).

CHAPTER 2

GREAT BLUE HERON REPRODUCTION

INTRODUCTION

Many factors have been shown to affect Great Blue Heron reproduction including nest placement (Simpson et al. 1987), colony size (Forbes et al. 1985; Thomas 1986), distance between foraging site and colony (Simpson et al. 1987), clutch size (Henny and Bethers 1971; Tomlinson 1975; Rodgers 1980; Tremblay and Ellison 1980; Pratt and Winkler 1985), nest initiation (Pratt and Winkler 1985; Butler 1995), nestling mortality due to starvation (Pratt 1972; Collazo 1981; Quinney 1983; Mock 1985; Sullivan and Payne 1988) and falls from the nest (Butler 1995), human disturbances (Simpson et al. 1987), heavy rain storms (Kelly et al. 1993), fire (Rickard pers. comm.), and predation (Lopinot 1951; Bayer 1979; Kelsall and Simpson 1980). Contaminants also affect reproduction in avian piscivores, such as mercury (Connors et al. 1975; Gochfeld 1975; Koeman et al. 1975; Heinz 1976; Finley and Stendell 1978; van der Molen et al. 1982), lead (Kendall and Scanlon 1981; Kendall et al. 1982; Burger and Gochfeld 1985, 1988; Burger 1990), fluoride (Hoffman et al. 1985; Pattee et al. 1988), selenium (Hoffman and Heinz 1988; Skorupa and Ohlendorf 1991), halogenated aromatic hydrocarbons (Fitzner et al. 1988; Moul et al. 1989; Bellward et al. 1990; Gilbertson et al. 1991; Hart et al. 1991; Nosek et al. 1992; Sanderson et al. 1994a, b), and organochlorine compounds (Fitzner et al. 1988; Ohlendorf and Marois 1990; Custer et al. 1997).

The primary objective of this study was to determine Great Blue Heron productivity along the Columbia River adjacent to the Hanford Site, and to identify factors potentially affecting reproductive success. Little is known about the reproductive success and factors affecting reproductive success in Great Blue Herons nesting on the Hanford Site. Reproductive success in this study is defined as the number and/or proportion of nestling herons fledged. Therefore, I compared

colony size, nest eggshell thickness, brood size, incubation initiation, adult foraging distance, and hatch order to either colony, nest, or individual fledging success of nestling herons. Although concern with contaminants moving through the aquatic food chain was one reason Great Blue Herons were studied, contaminants were not investigated in this study. Estimates of reproductive success, however, will provide needed baseline data for future contaminant studies. In addition, this information will be useful for a more complete understanding of the overall factors affecting Hanford heron reproductive success.

The second objective of this study was to determine mean eggshell thickness differences among Great Blue Heron colonies, using cast eggshells. Certain contaminants, such as organochlorines (Ohlendorf and Marois 1990; Custer et al. 1997) and PCB's (Henny et al. 1984; Fitzner et al. 1988), are known to cause eggshell thinning. Estimates of eggshell thickness will be compared to reported values known to cause reproductive impairment due to eggshell thinning. Cast eggshells provide an inexpensive, non-lethal, and fairly unobtrusive way of assessing differences among colonies. If differences in mean eggshell thickness exist among colonies, this will aid in determining which colonies should be selected for future studies. However, if colony differences do not exist, this will still provide valuable information for continued monitoring of the aquatic ecosystem with the passage of time.

STUDY AREA

Approximately 80 km of free-flowing Columbia River, in southcentral Washington, borders the 1,482 km^2 U.S. DOE Hanford Site on the west and south (Rogers and Rickard 1988), and state and federal wildlife administered lands on the north and east (Fig. 2). This area is mostly undeveloped and access on the Hanford Site and federal wildlife lands is limited to authorized personnel. The Hanford Site was established in 1943 as an isolated area for the production of plutonium, used in nuclear weapons (Fitzner and Gray 1991). Currently there are seven decommissioned nuclear reactors on site (100F, 100H, 100D, 100N, 100K 100B, and 100C) located along the western shore of the river (Fig. 2). Since the shut down of these reactors, the major function of DOE Hanford has switched from nuclear weapons production to contamination cleanup of the surrounding areas (Geist 1995).

Climate of this semi-arid land consists of hot, dry summers and moderately cold, wet winters. Annual precipitation averages 16.5 cm, but ranges from 7-30 cm (Stone et al. 1972). Vegetation in this shrub-steppe region consists primarily of Big Sagebrush, (*Artemisia tridentata*), Sandberg's Bluegrass, (*Agropyron spicatum*), and Cheatgrass Brome, (*Bromus tectorum*), in the uplands (Daubenmire 1970). Mature trees are scarce along the narrow riparian zone of the Columbia River (Rickard et al. 1981) consisting mainly of shrub Willows (*Salix* spp.), Cottonwoods (*Populus* spp.), and Mulberry (*Morus alba*).

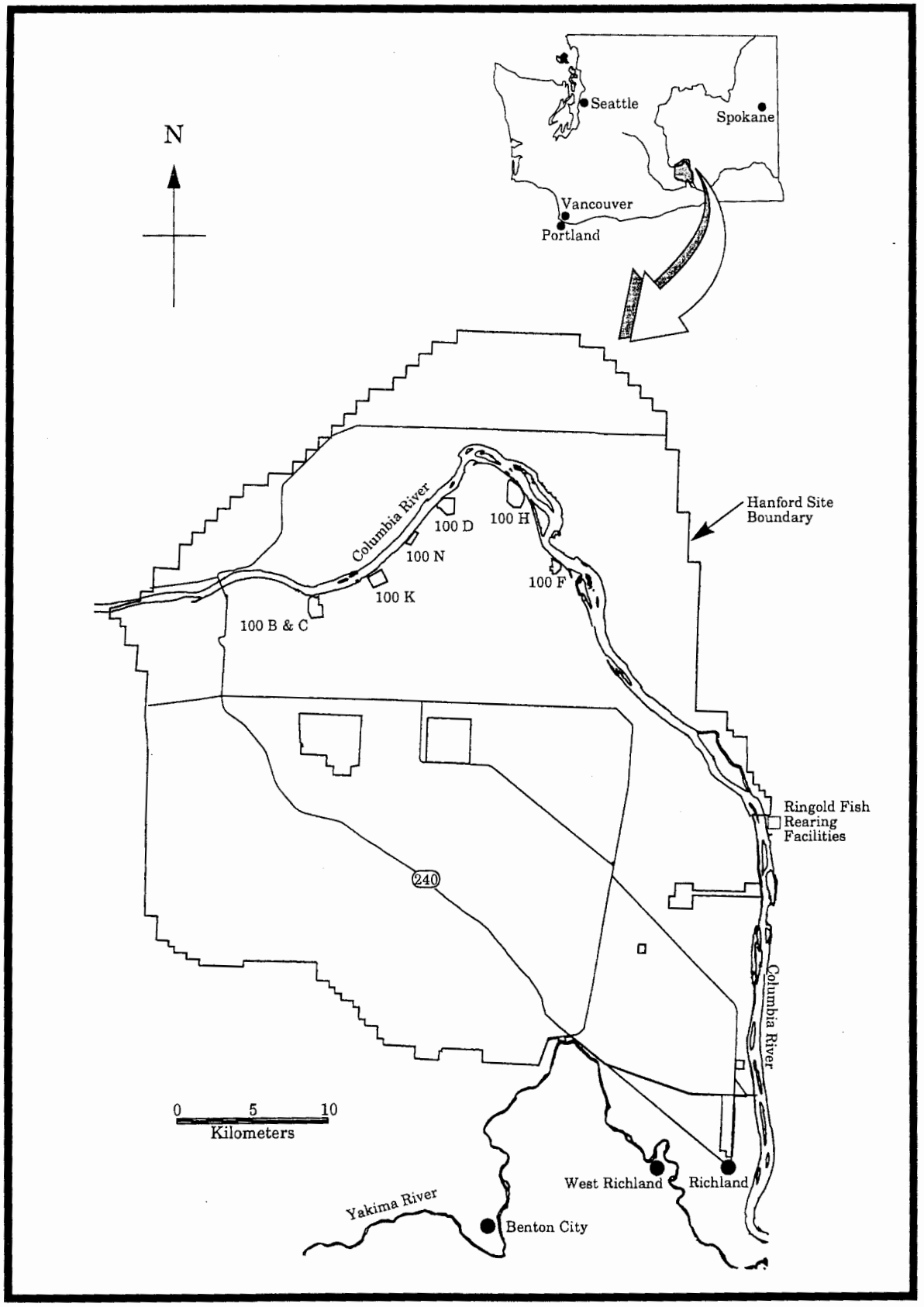

Figure 2. The U.S. Department of Energy's Hanford Site, Richland, Washington.

METHODS

FIELD WORK

Nine active Great Blue Heron colonies, all near the Columbia River shore, were distributed within the Hanford Site Boundary in 1995 and/or 1996 (Fig. 3). Five of these colonies were chosen for study on the basis of their location, access, visibility, and size (largest size for that colony indicated after colony abbreviation): Island 12 (POW:12), Savage (SAV:6), Hanford Townsite (HTS:1), Franklin White Bluffs (FWB:38), and Vernita (VER:3) (Table 3). Nest locations at each colony were mapped and numbered for individual identification prior to each nesting season. Near daily surveys (hereafter referred to as daily surveys) of nesting herons were conducted from April through August 1995 and from March through July 1996 to locate active nests (i. e. incubating adults), identify brood size, determine fledging success, and to coordinate boat surveys used to track foraging adults. I increased the number of daily surveys from 4.9/week in 1995 to 6.0/week in 1996 in order to increase data collected and account for difficulties associated with reproductive success estimates in colonial nesters (Erwin and Custer 1982; Pratt and Wrinkler 1985; Frederick et al. 1993).

Nests were periodically visited during the beginning of incubation using a ladder and/or a video camera mounted on an extending pole (Fig. 4); (Appendix A). These visits were necessary to view nest interiors and determine the day the first egg was laid within a nest. I visited colonies, to mark eggs, once in late April. I used either a 62-foot or 48-foot aerial platform to gain access to the nests (Fig. 5). The poles of each egg, from those nests that could be safely reached, were individually coded using a permanent marker (see Custer 1991), allowing identification of nests in which cast eggshells came from.

Newly hatched marked and unmarked eggshells were collected from the ground during colony visits for eggshell thickness measurements. Colony visits

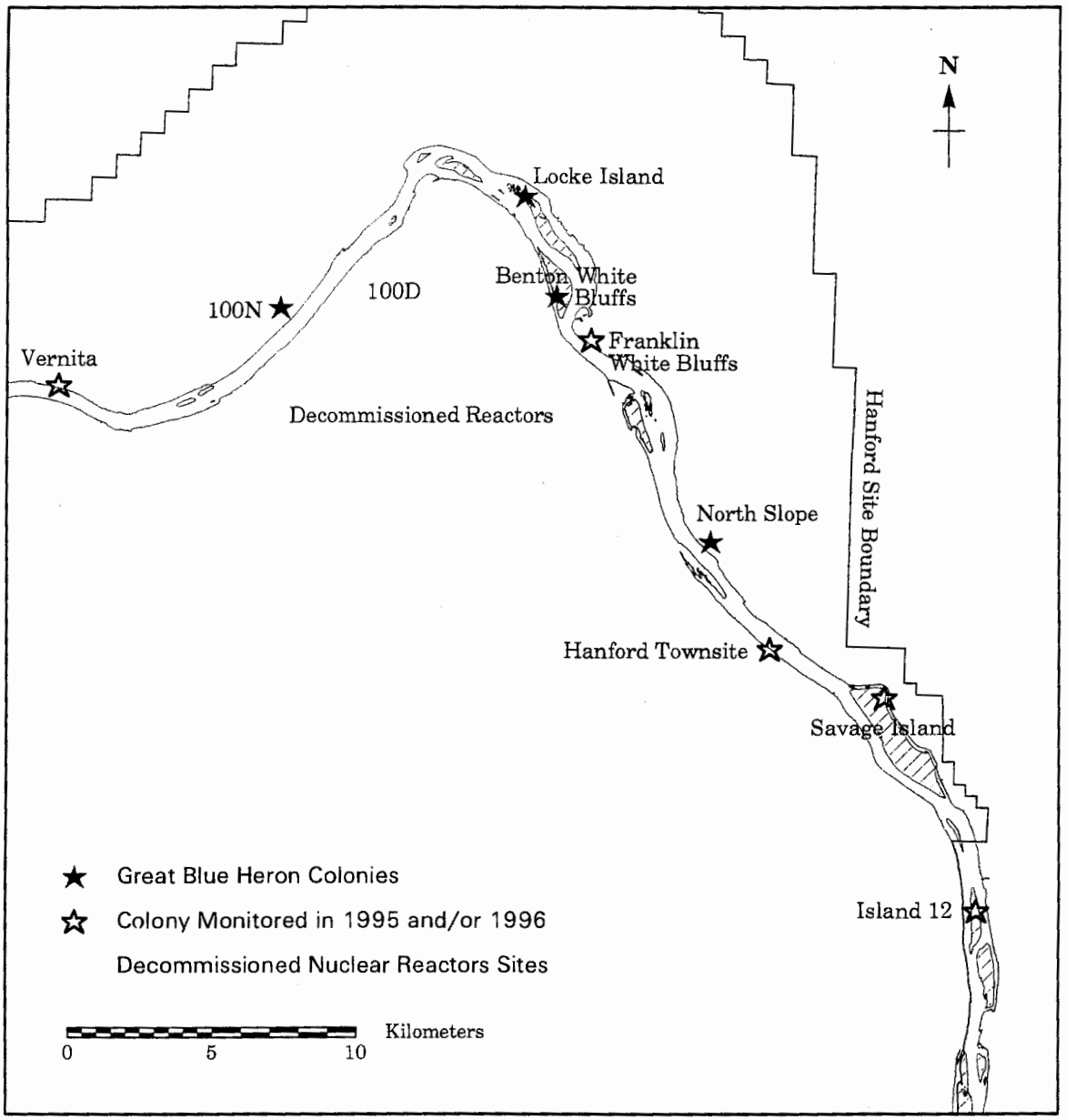

Figure 3. Great Blue Heron colonies active in 1995 and/or 1996 along the Columbia River adjacent to the Hanford Site, Washington.

Table 3. Great Blue Heron nest substrate, colony activity, and selection criteria of observed colonies along the Hanford Reach, Washington during 1995 and 1996. (* study sites)

Colony ID	Nesting Substrate[a]	Active[b]	Criteria for Selection
Vernita*	Black Locust	Both Years	Access, location, size, and easy to observe
100N	Steel Powerline	Both Years	Difficult to access, limited visibility, and small size
Locke Island	Black Locust	1995	Difficult to access
Benton White Bluffs	White Poplar	1995	Lack of access, Bald Eagle roost site
Franklin White Bluffs*	Black Locust	Both Years	Access, location, size
North Slope	Siberian Elm	1995	Difficult to access and limited visiblilty
Hanford Townsite*	Siberian Elm	1996	Size and easy to observe
Savage Island*	Black Locust	Both Years	Access, location, size, and easy to observe
Island 12*	Steel Powerline	Both Years	Location, size, and easy to observe

[a] Type of structure in which nests were placed.
[b] At least one pair of adult herons laying a full clutch of eggs.

Figure 4. Video camcorder used in Great Blue Heron study, near Richland, Washington.

Figure 5. Aerial platform used in Great Blue Heron study near Richland, Washington.

increased from one to three times a week depending on peak hatching period and the number of nests with unhatched eggs. Eggshells were dried at room temperature (20 ± 1° C) for a minimum of one month prior to measuring. Eggshell thickness was calculated from an average of three measurements taken at the equator of each eggshell (Fitzner et al. 1988) using a ball-micrometer graduated in 0.001 inches, and then converted into millimeters (mm).

Attached membranes were removed prior to measurement, because most eggshell membranes were either absent or a substantial portion was missing at the time of collection. To allow direct comparisons with Great Blue Heron eggshell thickness measurements that included membranes from other studies, I calculated mean membrane thickness from 11 eggshells collected between 1996 and 1997. Due to the small amount of membrane present, only one thickness measurement could be taken on each membrane using a ball micrometer. I considered mean membrane thickness as an average thickness of all eggshell membranes measured.

Aerial platforms were used to access nests and to tag nestlings. Tagging occurred when the oldest nestlings in a colony were between four and five weeks of age. This schedule was designed to reduce nestling mortality due to premature flight (Butler pers. comm.). Each tagged nestling was weighed, measured (i.e., culmen and tarsus), fitted with both patagial tags, and a numbered U.S. Fish and Wildlife Service (USFWS) aluminum leg band placed below the tarsometatarsal joint. In addition, 14 nestlings were fitted with either a 28 gram solar-powered, patagial transmitter or a 12.5 gram battery powered leg transmitter (Appendix A). Patagial transmitters (Fig. 6) were attached to the patagium, whereas leg transmitters were attached to an aluminum band with braided nylon fishing line and epoxy glue, and then fitted around the tibiotarsus in a similar manner as USFWS leg bands. Patagial tags were constructed as a modified version of those described by Kautz and Seamens (1992) in either orange, white, red, green, or blue, with number/letter

Figure 6. Patagial transmitter used in Great Blue Heron study near Richland, Washington.

combinations for individual visual identification (Fig. 7). Tags were attached to the patagium by a male and female tag (Appendix A). Each sibling from a nest was given a different colored patagial tag to increase the distance from the colony and efficiency which nestlings were identified, thus reducing potential influence due to observer presence and misidentifications.

Both marked and unmarked nestlings were observed daily starting at 0500 hours to avoid interference from heat waves while viewing with the spotting scope. The observer remained at the colony until all nestlings were accounted for. Nestling mortality was assumed the first day a bird was absent during a parental feeding period, prior to being considered fledged (leaving the nest vicinity).

Adults were captured at the salmon/steelhead fish-rearing facilities at Ringold (Fig. 8), from 22 January to 11 March 1996, using a padded leg-hold trap (Appendix A) (King et al. 1994). I trapped adults at this time of the year to avoid distressing nesting adults, however, it was probable that not all adults nesting in the study area were present during trapping. Traps were checked three times a day between 22 January 1996 and 14 February 1996. To reduce capture related mortalities, traps were checked four times a day from 15 February 1996 through 11 March 1996. Captured adults were fitted with a patagial tag, leg band, and a 32 gram dual power (solar/battery) patagial transmitter (Appendix A), attached in the same manner as for nestlings. Foraging sites of nesting adults were determined by tracking birds and by following unmarked adults from the colony to their first river landing site or foraging location, with a boat (Appendix A).

Boat surveys were coordinated with daily ground surveys. This allowed the land observer to relay the nest number of a departing adult, determined from the nestlings it fed (i.e. nest number), to the boat observer, via cellular phone. I assumed that the place where the bird first landed was representative of the distance traveled between the colony and the foraging site (Custer and Osborn

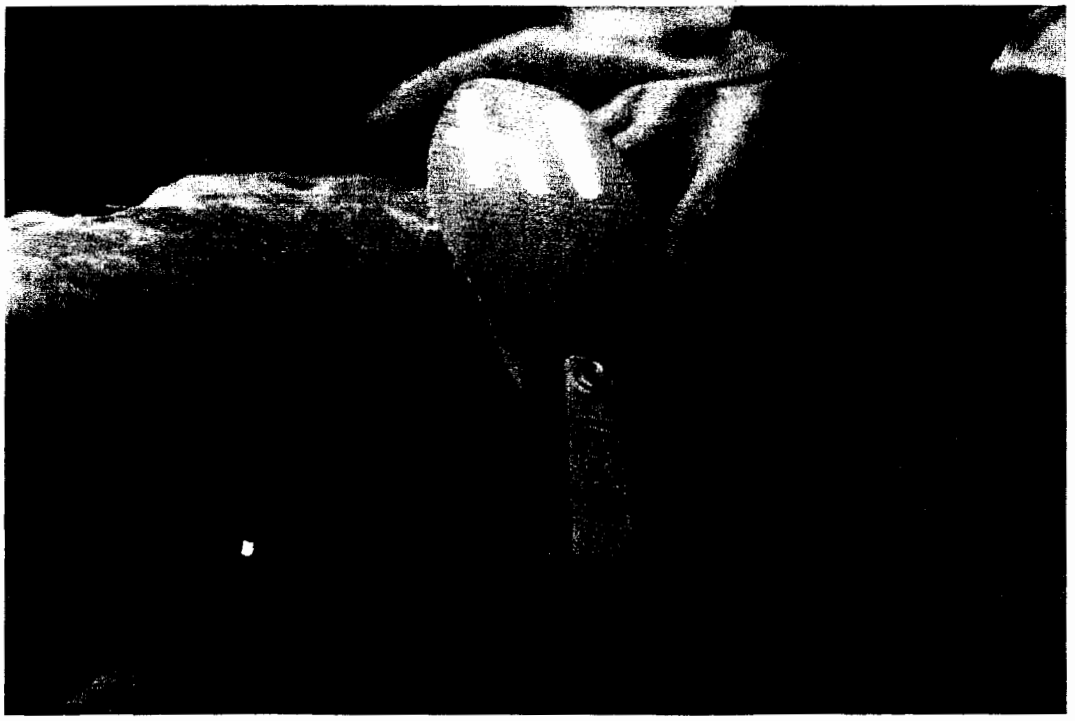

Figure 7. Patagial tag used in Great Blue Heron study along the Hanford Site, Richland, Washington during 1995-1996.

Figure 8. Great Blue Heron caught in a leg-hold trap at a fish rearing facility near Richland, Washington, 1996.

1978). I followed the first adult leaving the colony until it landed or flew out of sight, before returning to the colony to follow the next departing adult. Because of differing size and nesting stage (I.e. incubating, hatchlings, or nestlings), colonies were not surveyed from the boat uniformly. Boat traffic along this portion of the Columbia River is common, thus it was assumed the chase boat did not cause unusual disturbance to the herons. However, some bias in adult foraging locations was created by our inability to keep pace with Franklin White Bluff adults that flew upriver (Fig. 3). All locations were marked on a 7.5' U.S. Geological Survey topographic map with the colony and nest number from which it came. Foraging site locations were converted into Universal Transverse Mercator (UTM) coordinates using Geographical Information Systems (GIS).

DATA ANALYSIS

Fledging Success

I considered marked nestlings to be fledged the first day they were seen out of the nest (usually on a nearby limb). Because of difficulties in identifying individuals after leaving the nest, unmarked nestlings were considered fledged the first day they were found standing on the rim of the nest. Inferring reproductive success at this early mobile stage may be inaccurate and telemetry is currently the best option for measuring late nestling survival (Frederick et al. 1993). In 1995, I radio-tagged 14 nestlings from nests with different numbers of siblings and of varying hatch order (age structure within a nest due to asynchronous hatching) to determine survival during the post-mobile phase, and to determine movements after leaving the colony.

Thirteen (93%) of the radio transmittered nestlings survived to the fledging stage. All surviving radio-tagged nestlings rapidly dispersed out of the study area, confirming their fledging status. Furthermore, I continually observed patagial

marked nestlings during the post-mobile phase (after I considered them fledged). Three patagial marked nestlings (7.3 percent) that were considered fledged, never left the colony. From this information I determined that late nestling stage mortality was minimal and could be determined from patagial marked nestlings. Thus, I did not use telemetry in 1996. I defined nest fledging success as the number of young fledged per nest and colony fledging success as the mean number fledged per nest within a colony. Proportion fledged per year and proportion fledged per nest was calculated as the total number fledged divided by the number present at three weeks of age for year and nest respectively. Fledging success estimates of marked and unmarked nests were pooled whenever possible.

Statistical analyses were conducted using the statistical analysis software JMP® version 3.1 (SAS Institute 1995) to run standard least squares, grouped means one-way analysis of variance (ANOVA), nominal logistics, and Tukey-Kramer pairwise comparison, testing for differences in fledging success. I analyzed the dependent variable, fledging success, individually against the independent variables: year, nest eggshell thickness, colony size, incubation initiation, brood size, hatch order, and forage distance, as well as appropriate yearly interaction terms.

Annual Fledging Success

I defined annual fledging success as the average number of young fledged per year, from nests with at least one young surviving to three weeks. Both annual nest fledging success and annual proportion fledged per nest were compared between years using grouped means, one-way ANOVA.

Colony Size

I defined colony size, as the number of active nests in a colony. I considered an active nest as one with a full clutch of eggs, incubated at least 14 consecutive days (determined from daily surveys of adult behavior). I used 14 days because the largest clutch size reported for Great Blue Herons is seven eggs (Bent 1926) with a

laying interval between eggs of two day (Pratt 1970). I calculated fledging success for a colony by dividing the number of young fledged by the number of active nests observed within that colony. Because herons do not show mate, nest, and colony fidelity between years (Simpson 1984; Simpson et al. 1987), I considered colonies as separate observations between years for analyzing colony size. Colony size was analyzed using standard least squares.

Nest Eggshell Thickness

I considered mean nest eggshell thickness as the average thickness of all marked eggshells collected from the same nest in 1996. Five abandoned or predated nests with collected eggshells were excluded from analysis because these factors directly influenced fledging success and were assumed to be unrelated to eggshell thickness. Mean nest eggshell thickness was compared to corresponding nest fledging success using standard least squares.

Incubation Initiation

Herons usually begin incubation after the first egg is laid (Lack 1968; Pratt 1970; Quinney 1982; Mock 1985), so I defined incubation initiation as the day the first egg was laid. Date of incubation was determined by observing the date the first egg appeared, or by identifying a recently laid egg (Custer 1991), and extrapolating backwards two days for each egg except one. These dates were then converted to Julian dates and broken into five periods. The first four incubation periods were at 10 day intervals beginning with the earliest Julian date, and the fifth period contained the remaining dates. A total of six nests were excluded from analysis over the two year period: four partially or completely predated nests, and two abandoned nests due to repeated Red-tailed Hawk (*Buteo jamaicensis*) harassment. I used grouped means one-way ANOVA to test for differences in nest fledging success among periods. Tukey-Kramer pairwise comparison was used to test for period differences after a significant F-test.

Brood Size

I considered brood size as the number of young per nest at approximately three weeks of age, determined from daily surveys. At this time, nestlings could stand in the nest (Pratt 1970) during parental feedings and easily be counted. I calculated the proportion fledged for each nest by dividing the nest fledging success by the brood size. I analyzed brood size against both nest fledging success and proportion fledged using standard least squares.

Hatch Order

Hatch order for this study was defined as the age structure within a nest (i.e. a brood size of four would have first, second, third, and fourth hatched) at the time of tagging . I estimated nest hatch order from the relative size (i.e. weight, culmen, and tarsus length) of each tagged nestling (Custer and Peterson 1991; Butler pers. comm.). Daily surveys were used to identify survival of marked nestlings to fledging. I analyzed hatch order against individual fledging success for each age group using nominal logistics.

Forage Distance

I defined forage distance as the mean distance traveled from the colony to foraging sites for a pair of adults from a nest. Because of the difficulties associated with obtaining adult locations away from the river, I considered adult foraging sites as any location where adults were followed or located standing next to or in the Columbia River. I calculated mean foraging distance by averaging the distance from all foraging sites to the colony for a given pair. I examined the influence of mean foraging distance to nest fledging success using standard least squares.

Colony Eggshell Thickness

Nest eggshell thickness (mean eggshell thickness of all marked eggshell from a nest) was used to calculated colony eggshell thickness (mean eggshell thickness

of all known nests from a colony). Mean eggshell thickness of all unmarked eggshells collected from a colony were treated as another nest in that colony. I considered mean eggshell thickness for a colony as the average of all eggshells collected from a colony. Statistical analyses were conducted using Statistical Analysis System (SAS) (SAS 1985). I used SAS to run the General Linear Models (GLM) procedure, using eggs from known nests; from known colonies, to test differences between nests within a colony, and then used nests within a colony to test colony differences. Comparison between mean colony eggshell thickness were analyzed using Tukey-Kramer pairwise comparisons after a significant F-test (Sokal and Rohlf 1981).

I calculated mean eggshell thickness for four colonies where eggshells were collected during both years, by taking the annual average eggshell thickness of all eggshells collected from a given colony. I analyzed mean colony eggshell thickness and pairwise comparisons, using statistical analysis software JMP® version 3.1 (SAS Institute 1995) to run standard least squares, to test differences between years, colonies, and to test appropriate interaction terms. Tukey-Kramer pairwise comparison was used to test colony differences after a significant F-test.

I measured mean membrane thickness of 11 eggshells collected from 1996 through 1997. Membrane thickness ranged between 0.053 and 0.071 mm with a mean membrane thickness of 0.062 mm (standard error = .000172 mm). Mean membrane thickness was added to mean colony eggshell thickness when comparing with past studies, to allow for direct comparisons.

RESULTS

I caught 45 Great Blue Herons, 16 adults and 23 subadults, from 22 January 1996 to 11 March 1996 (0.9/day). Capture myopathy and/or hypothermia may have resulted in mortality observed for two adults and four subadult herons. No mortalities occurred after increasing the trap checking frequency from three to four times daily. Four of sixteen marked adults (25%) successfully nested along the Hanford Reach, while the remaining 12 adults dispersed from the area between March and April.

Colonies were visited during each daily survey. Eighty-three daily surveys were conducted from 18 April 1995 to 11 August 1995 (4.9/week) and 114 surveys were conducted from 25 March to 29 July 1996 (6.0/week) to determine reproductive success (fledged per nest).

Fledging Success

I determined fledging success for 190 nestlings from the nine colonies observed. I estimated 175 nestlings fledged from 66 nests (89 from 33 marked nests, and 86 from 33 unmarked nests) between June 1995 and August 1996 (Table 4). Of the 89 marked nestlings considered fledged, 4.5% (four birds) never left the colony. Analysis of nest fledging success using standard least squares indicated no significant difference between years at marked nests ($F = .1929$, 1 df, $P = .66$), or between marked and unmarked nests ($F = .1716$, 1 df, $P = .68$).

Annual Fledging Success

During daily surveys, I estimated nest fledging success of 19 and 47 nests, with young 21 days of age, in 1995 and 1996 respectively. Results indicated no difference in the yearly nest fledging success ($F = .0133$, 1 df, $P = .9085$) (Table 5),

Table 4. 1995 and 1996 fledging success of marked and unmarked nestling Great Blue Herons along the Hanford Site, Washington.

	Number Marked	Number Fledged	Nests Observed	Fledged per Nest
Marked				
1995	65	50	19	2.63
1996	39	39	14	2.79
pooled	104	89	33	2.70
Unmarked				
1996		86	33	2.61
Total	104	175	66	2.65
Adjusted[a]		167	66	2.53

[a] Fledging success was adjusted to account for 4.5% nestling mortality in the post-mobile stage.

but show annual proportion fledged per nest was significantly higher in 1996 (F = 11.4537, 1 df, .0012) (Fig. 9).

Colony Size

I observed a total of nine Great Blue Heron colonies were observed between the 1995 and 1996 nesting period, four and five colonies respectively. Colony size, determined by the number of active nests, ranged from one to 38 (Table 6). Fledging success at different sized colonies was not significantly different (F = .9363, 1 df, P = .3655).

Nest Eggshell Thickness

Mean nest eggshell thickness was calculated for 17 nests, using 40 marked eggshells, from four colonies. One to five eggshells were collected from a single nest. Mean nest eggshell thickness was compared to nest fledging success and was not statistically significant (F = 2.0385, 1 df, P = .1738), even though eggshell thickness was greatest for the nest that fledged four young (Fig. 10).

Incubation Initiation

Incubation starting dates were estimated for 18 and 46 active nests in 1995 and 1996 respectively. Incubation initiation went from 23 March to 31 May in 1995, and from 15 March to 26 May in 1996. Incubation periods were significant (F = 5.5166, 4 df, P = .0008) when analyzed against nest fledging success. Results of Tukey-Kramer multiple comparison shows fledging success was higher in period two than periods four and five, period one was significantly higher than period five, and period three was intermediate (Table 7).

Brood size

I estimated the brood size (young per nest at approximately 21 days of age) of 66 Great Blue Heron nests, during daily surveys along the Hanford Site between

Table 5. Annual brood size and fledging success differences for Great Blue Herons adjacent to the Hanford Site, Washington.

Year	Sample Size	Mean Brood Size[a]	sd[b]	Mean Success[c]	sd[b]
1995	19	3.42	0.8377	2.63	1.1161
1996	47	2.87	0.9235	2.66	0.7879

[a] Average young per nest at approximately three weeks old.
[b] Standard deviation.
[c] Average number of young fledged per nest.

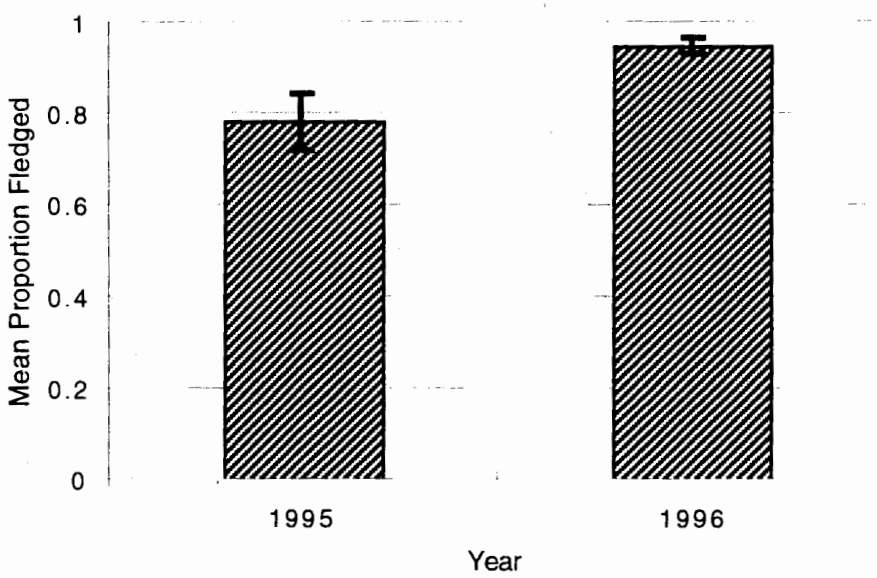

Figure 9. Mean proportion of nestling Great Blue Herons fledged per nest ± 1 standard error, on the Hanford Reach, Washington in 1995 and 1996.

Table 6. Mean young fledged per active Great Blue Heron nest along the Columbia River adjacent to the Hanford Site, Washington, in 1995 and 1996.

Colony	Year	Active Nests[d]	Nests Observed	Mean Number Fledged per Nest
FWB[a]	1995	34	10	2.7
	1996	38	36	2.61
HTS[b]	1995	NA[e]	0	0
	1996	1	1	2
POW[c]	1995	12	2	3
	1996	7	7	1.43
Savage	1995	6	4	2.75
	1996	6	6	3
Vernita	1995	3	3	2
	1996	3	3	0.33
TOTAL		110	72	2.43

[a] FWB = Franklin White Bluffs.
[b] HTS = Hanford Townsite.
[c] POW = Island 12.
[d] Active Nest is any nest incubated for at least 14 consecutive days.
[e] NA = not active

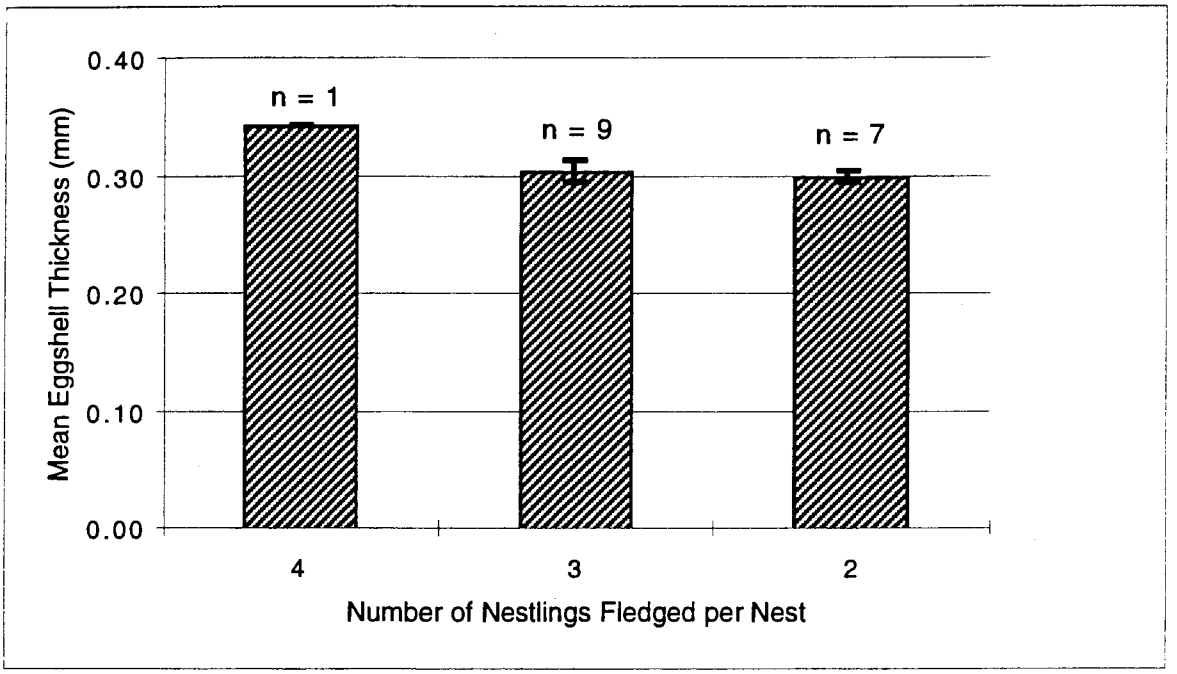

Fig. 10. Mean nest eggshell thickness ± 1 standard error based on the number of nestling Great Blue Herons fledged per nest along the Columbia River, adjacent to the Hanford Site, Washington, in 1996.

Table 7. Multiple comparisons of incubation initiation periods from Great Blue Herons nesting along the Columbia River, adjacent to the Hanford Site, Washington, 1995 through 1996.

Success[a]	sd[b]	Similarity[c]			Sample Size	Period	Julian Date[d]
3.20	0.6761	A			15	2	84-93
3.13	0.8345	A	B		8	1	74-83
2.75	0.6387	A	B	C	20	3	94-103
2.31	0.7511		B	C	13	4	104-113
2.00	0.7559			C	8	5	114-151

[a] success = mean number of young fledged per nest.
[b] sd = standard deviation.
[c] Periods with letters in the same verticle column are not significantly different.
[d] 97 days = 7 April and 133 days = 13 May

April 1995 and August 1996. Brood size ranged from one to five nestlings per nest. Larger broods had a significantly higher nest fledging success with a significantly lower proportion fledged per nest than smaller nests ($F = 59.9539$, 1 df, $P < 0.0001$) (Table 8) and ($F = 7.5482$, 1 df, $P = .0078$) (Fig. 11) respectively.

Hatch Order

A total of 104 nestling herons were tagged, 65 and 39 during 1995 and 1996 respectively, from 33 nests (3.15 young/nest). Ninety nestlings (87%) were individually marked with patagial tags, one was leg banded only, and the remaining 13 birds were unmarked. Typically these nestlings were either the youngest, (too small to tag) or oldest, (developed enough to avoid capture) individuals from a nest. Leg banded and unmarked young were still considered tagged because the rest of the nest was marked and I was able to distinguish these birds from their siblings. Fledging success was significantly higher for older siblings ($\chi^2 = 7.1351$, 3 df, $P = .0677$) (Fig. 12).

Forage Distance

Fifty-two boat surveys were conducted in conjunction with daily surveys from 23 May 1996 to 29 July 1996 (5.4/week), to estimate the distance adults traveled between the colony and their foraging sites. A total of 277 river foraging locations were obtained from 42 nests (Fig. 13). I determined 181 locations from adult departures and 87 locations from radio-telemetry. An additional eight (3%) adult foraging locations were obtained by following adults from their foraging sites back to the colony. Data from four marked adults contributed 37 percent of the foraging locations, with 15 and 87 locations coming from departures and telemetry locations respectively. Of 447 known adult departures from 48 nests (9.3/nest), 181 from 42 nests (4.3/nest), foraged along the Columbia River. Departures from the colony to

Table 8. Descriptive statistics of Great Blue Heron fledging success from different sized broods, along the Columbia River adjacent to the Hanford Site, Washington, between 1995 and 1996.

	Number of Nestling Great Blue Herons Fledged per Nest				
Brood Size[a]	Mean	Sample Size	Standard Deviation	Minimum	Maximum
1	1.00	3	0	1	1
2	1.94	17	0.24	1	2
3	2.82	22	0.39	2	3
4	3.22	23	1.00	0	4
5	3.00	1	NC[b]	3	3
Total	2.65	66	0.89	0	4

[a] Brood size = the number of nestlings alive per nest at approx. 21 days of age.
[b] NC = unable to calculate standard deviation due to sample size.

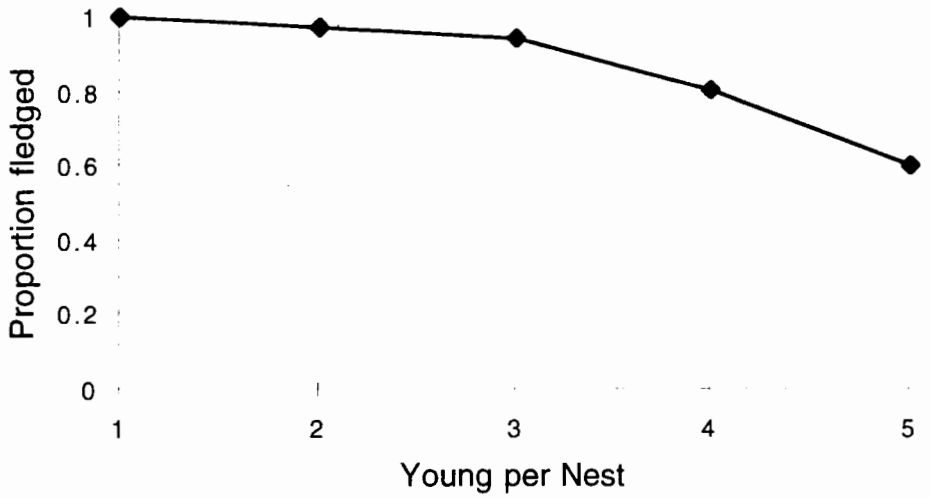

Figure 11. Mean proportion fledged per nest for Great Blue Heron nests with differing numbers of young per nest at approximately 21 days old along the Hanford Site, Washington.

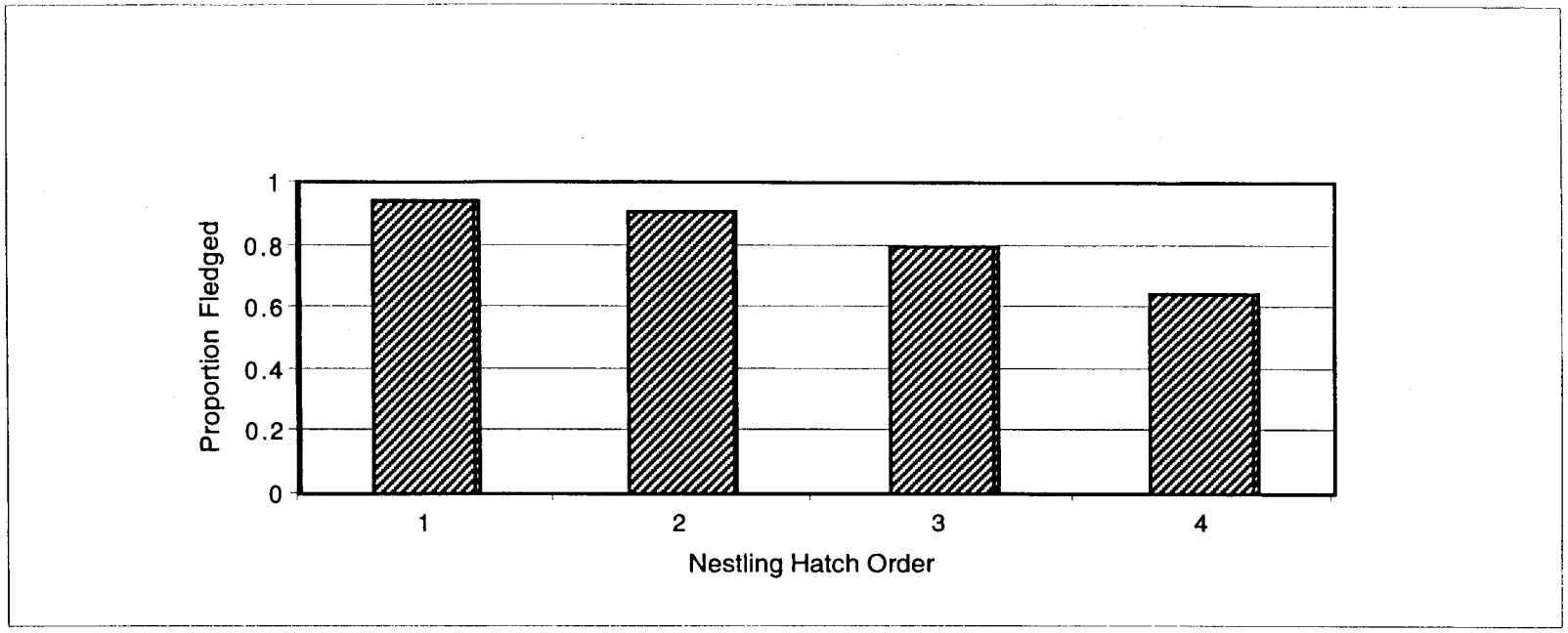

Figure 12. Fledging success of different aged nestling Great Blue Herons near the Hanford Site, Washington, during 1995 and 1996.

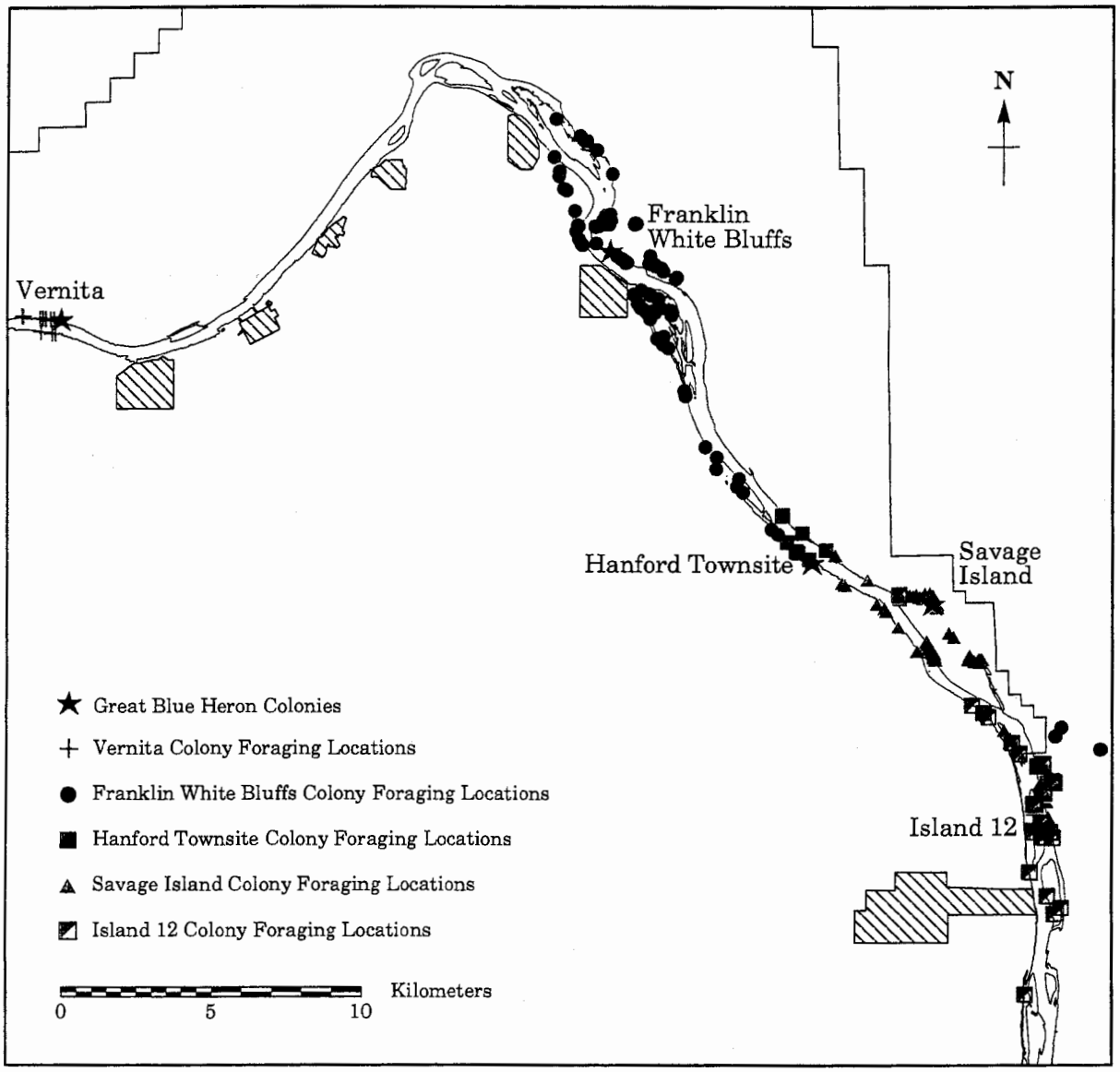

Figure 13. Adult Great Blue Heron foraging locations along the Columbia River adjacent to the Hanford Site, Washington from April through August 1996.

the river ranged from 0 (6 nests) to 100 percent (5 nests). I tested the relationship of mean nest foraging distance to nest fledging success and found mean distance adults foraged from the colony was not significant (F = .5503, 1 df, P = .4625).

Eggshell Thickness

Ninety-one eggs, from 26 nests, were marked in five different colonies in 1996. Fifty-seven newly hatched eggshells (63%) were found in a condition useable for measurement of eggshell thickness. Twenty-two (85%) of the nests had at least one eggshell collected from them. Fifty-three unmarked eggshells from three colonies were also collected in 1996 and the mean eggshell thickness of all unmarked eggshells from a colony was added as another nest in that colony. Mean eggshell thickness among colonies and nests within a colony were significantly different from one another (F = 3.4431, 4 df, P < .05) and (F = 2.213, 21 df, P < .01) respectively. Tukey-Kramer multiple comparisons indicated that Savage (SAV) had the highest mean eggshell thickness, Franklin White Bluffs (FWB); Island 12 (POW); and Vernita (VER) had the lowest mean eggshell thickness, and Hanford Townsite (HTS) had intermediate eggshell thickness (Table 9).

Mean colony eggshell thickness of 36 eggshells collected in 1995 at FWB, POW, SAV, and VER were compared to 107 eggshells collected at those same colonies in 1996 (Table 10). Mean eggshell thickness between years and colonies were both significantly different (F = 4.6924, 1 df, P = .032), and (F = 5.5609, 3 df, P = .001) respectively, with year and colony interaction marginally significant (F = 2.3743, 3 df, P = .0730). Interannual variation in mean eggshell thickness at a colony was marginally significant at Vernita (VER) (F = 4.1799, 1 df, P = .0712) and Island 12 (POW) (F = 3.0796, 1 df, P = .0915) (Fig. 14). Tukey-Kramer multiple

Table 9. Multiple comparisons of mean colony eggshell thickness from Great Blue Herons nesting along the Columbia River, adjacent to the Hanford Site, Washington, 1996.

Colony	Mean Thickness[d]	sd[e]	Minimum	Maximum	Similarity[f]		Sample Size
Savage	0.337	0.019	0.298	0.367	*		12
HTS[a]	0.305	0.013	0.292	0.318	*	*	3
Vernita	0.303	0.028	0.271	0.351		*	9
FWB[b]	0.299	0.023	0.251	0.362		*	68
POW[c]	0.298	0.023	0.256	0.346		*	18

[a] HTS = Hanford Townsite.
[b] FWB = Franklin White Bluffs.
[c] POW = Island 12.
[d] Eggshell thickness measurements in (mm)
[e] sd = standard deviation.
[f] Colonies with asterisks in the same vertical column are not significantly different.

Table 10. Descriptive statistics of eggshell thickness at four Great Blue Heron colonies near the Hanford Site, Washington, during 1995 and 1996.

Colony		Sample Size	Mean Eggshell Thickness (cm)	Standard Deviation	Minimum	Maximum
FWB[a]						
	1995	23	0.294	0.0318	0.216	0.353
	1996	68	0.299	0.0233	0.251	0.362
Island 12						
	1995	9	0.313	0.0128	0.294	0.333
	1996	18	0.298	0.0233	0.256	0.346
Savage						
	1995	2	0.348	0.0594	0.306	0.390
	1996	12	0.337	0.0178	0.298	0.367
Vernita						
	1995	2	0.346	0.0071	0.341	0.351
	1996	9	0.303	0.0282	0.271	0.351

[a] FWB = Franklin White Bluffs.

comparisons of colonies, again showed Savage (SAV) with a significantly higher mean colony eggshell thickness than VER, POW, and Franklin White Bluffs (FWB) (Fig. 14).

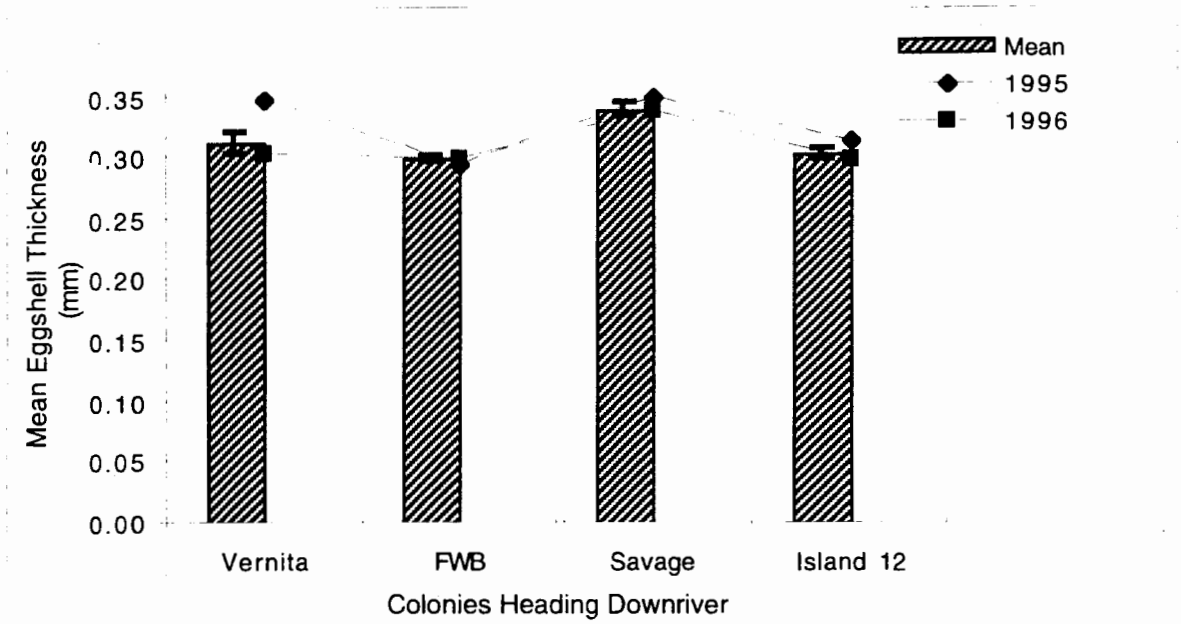

Figure 14. Average mean colony eggshell thickness ± 1 standard error and annual mean colony eggshell thickness at four different Great Blue Heron colonies heading downriver, along the Columbia River, adjacent to the Hanford Site, during 1995 and 1996.

DISCUSSION

Fledging Success

Mean number of young fledged per active Great Blue Heron nest in this study, is higher than those reported for other western U.S. herons, and intermediate of those reported for Great Blue Herons from Canada (Vermeer 1969; Pratt 1970; Henny and Bethers 1971; McAloney 1973; English 1978; Blus et al. 1980; Collazo 1981; Pratt and Winkler 1985) (Table 11). However, mean nestlings fledged per successful nest for this study, falls within the range previously reported for several Washington and Oregon Great Blue Heron colonies along the Columbia River in the 1970's (Blus et al. 1980) (Table 11).

I consider the fledging success determinations to be representative of the population in the study area. Erwin and Custer (1982) identified several problems with reproductive success estimates in colonial waterbirds, such as using unmarked adults, not visiting colonies daily, and inability to monitor all young until they fledge. In contrast, I visited colonies virtually daily (4.9/week in 1995 and 6.0/week in 1996), which allowed an accurate assessment of fledging success and nestling mortality. My methods were also more comprehensive. For example, I used marked nestlings to determine mortality on post mobile stage nestlings (Frederick et al. 1993). I also compared marked fledging success to unmarked fledging success estimates and found no difference in fledging success. These data indicate that future Hanford Great Blue Heron reproductive estimates can be adequately obtained from unmarked nestlings in the early mobile stage.

I did not ascertain the effects of observer disturbance on reproductive success. However, there was no nest abandonment attributed to observer presence or to colony visits. Furthermore, fledging success was higher for marked nests than

Table 11. Summary of reproductive success of Great Blue Herons in Western U.S. and Canada.

Location	Years	Percent of nests successful	No. young fledged per successful nest	No. young fledged per active pair	Source
Nova Scotia	1971	NA[a]	3.09	2.84	McAloney 1973
Southcentral Washington	1996	85	2.66	2.36	This study
Southern Alberta	1967-1968	NA[a]	2.51	2.2 to 2.3	Vermeer 1969
Western Oregon	1970	78	2.61	2.04	Henny and Bethers 1971
Northwestern Oregon	1975	NA[a]	2.32	1.96	English 1978
Northern Idaho	1978	89	2.2	1.95	Collazo 1981
Columbia River	1978	NA[a]	2.29-2.79	NA[a]	Blus et al. 1980
Central	1974	NA[a]	2.20	NA[a]	Pratt and Winkler 1985
California	1967-1968	76-82	NA[a]	1.5 to 1.7	Pratt 1970

[a] NA = not available

unmarked nests, so I assumed that observer influence on fledging success was small and consistent among nests and colonies.

Annual Fledging Success

Although nest fledging success was not significantly different between years (Table 5), the annual increase in proportion fledged (Fig. 9) indicates a decrease in nestling mortality and suggests increased fledging success in 1996. However, the mean number of young fledged per nest was nearly identical between years while the mean brood size was larger in 1995 (Table 5). I suspect the difference in proportion fledged per nest was a result of nestling mortality occurring before the number of young per nest were estimated (i.e. before nestlings were 21 days old) in 1996, and after this time in 1995. I also agree with previous findings, which indicate the majority of nestling mortality can occur between one and six weeks of age (Pratt 1970; Gill 1973; Collazo 1979, 1981; Pratt and Winkler 1985).

Colony Size

Great Blue Heron colony sizes along the Hanford Reach did not change markedly between study years (Table 6). Consistency in the size of heron colonies is typical from one year to the next (Custer et al. 1980). The exception to this would be the POW colony, which decreased in size 42% from 1995 to 1996 after a Red-tailed Hawk nested in the colony. Repeated harassment from the hawk led to the abandonment of three heron nests, which decreased colony fledging success 52% in 1996.

The highest colony fledging success was observed at Island 12 (POW) 1995 and Savage (SAV) 1996 (3 young/nest). These colonies were considerably smaller than the largest colony in this study (Table 6). These findings differ from earlier studies that indicated large colonies have higher reproductive success (Forbes et al.

1985; Thomas 1986). Using Forbes et al. (1985) colony size categories, mean number of young fledged for Hanford heron colonies were nearly identical, 2.70 and 2.69 for small and intermediate sized colonies respectively (Table 12). Fledging success for these smaller sized colonies are similar to those reported by Forbes et al. (1985) for larger sized colonies (Table 12). However, the difference in colony fledging success observed in this study, may be due to my small sample size of nine colonies.

I believe the close proximity of SAV and POW to the backwaters of Savage Island Slough, as well as the Ringold fish rearing facilities (Fig. 15), provided an enhanced local food source for these smaller colonies. I also believe these areas were consistently productive foraging areas because they remained unaffected by daily Columbia River water level fluctuations. These resources were not available to herons at the other colonies.

Nest Eggshell Thickness

To my knowledge, no other study has compared Great Blue Heron nest fledging success to thickness measurements of eggshells collected from the same nest. Although my results were not statistically significant, the single nest that fledged four young had the greatest eggshells thickness (Fig. 10). This may be the result of older healthier females which are more experienced at foraging and providing food for young. Further research with larger sample sizes would be required before any conclusion concerning the relationship between nest eggshell thickness and fledging success can be made.

Incubation Initiation

The decreased fledging success for Great Blue Herons initiating incubation late in the nesting season I observed, agrees with Pratt and Winkler (1985) and

Table 12. Comparison of fledging success from Great Blue Heron colonies of different sizes.

Mean fledged per nest[a]	Colony Size (number of occupied nests per colony) 1-30	31-55	56-236
British Columbia[b]	2.38	2.49	2.69
Hanford 1995-1996	2.70	2.69	NA[c]

[a] Mean number of young fledged per successful nest per colony.
[b] From Forbes et al. 1985.
[c] NA = not available.

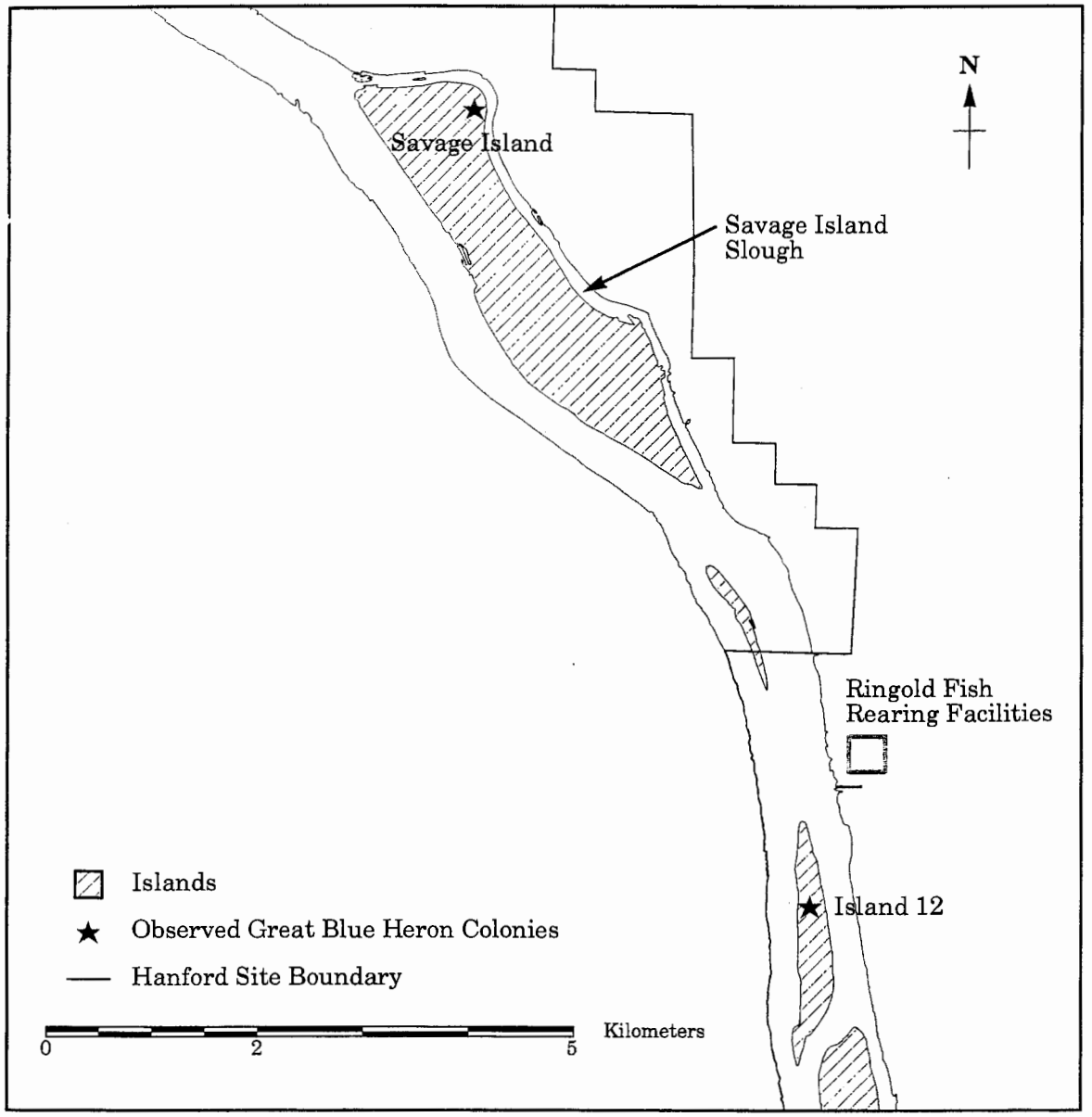

Figure 15. Location of Great Blue Heron colonies along the Hanford Site, Washington, in relation to stable foraging areas of Ringold Fish Hatchery and Savage Island backwaters.

Butler (1995) who also noted late nesting herons have lower reproductive success. Although I used ten day intervals in incubation initiation and Butler (1995) used weekly intervals of hatch date, his results show a similar decrease in fledging success after the second week of hatching.

Even though colonies started in different incubation initiation periods, fledging success also appears to gradually decrease within a colony after the second period (Fig. 16). However, small sample sizes in starting periods from colonies limit these data and further research is required before conclusions about colony differences can be made.

Butler (1995) attributed the lowered fledging success rate of late nesting herons to renesters. Although I agree that the observed difference in incubation initiation and fledging success is probably the result of smaller clutches laid later in the nesting season, I cannot infer as to whether this is the result of renesters (Jenni 1969; Wolford and Boag 1971; Batt and Prince 1979; Butler 1995), younger breeding birds (Lack 1968; Johnsgard 1973; Ryder 1980) or genetic control (Batt and Prince 1979).

Brood size

My analysis indicates that mean nest fledging success per brood size increased as the number of young per nest at 21 days of age increased (Table 8). Differences in the number of young fledged per nest that I observed among brood sizes support similar results reported for clutch size and reproductive success (Henny and Bethers 1971; Tomlinson 1975; Rodgers 1980; Tremblay and Ellison 1980; Pratt and Winkler 1985). I also found a significant relationship between proportion fledged per nest and brood size. These data show a negative

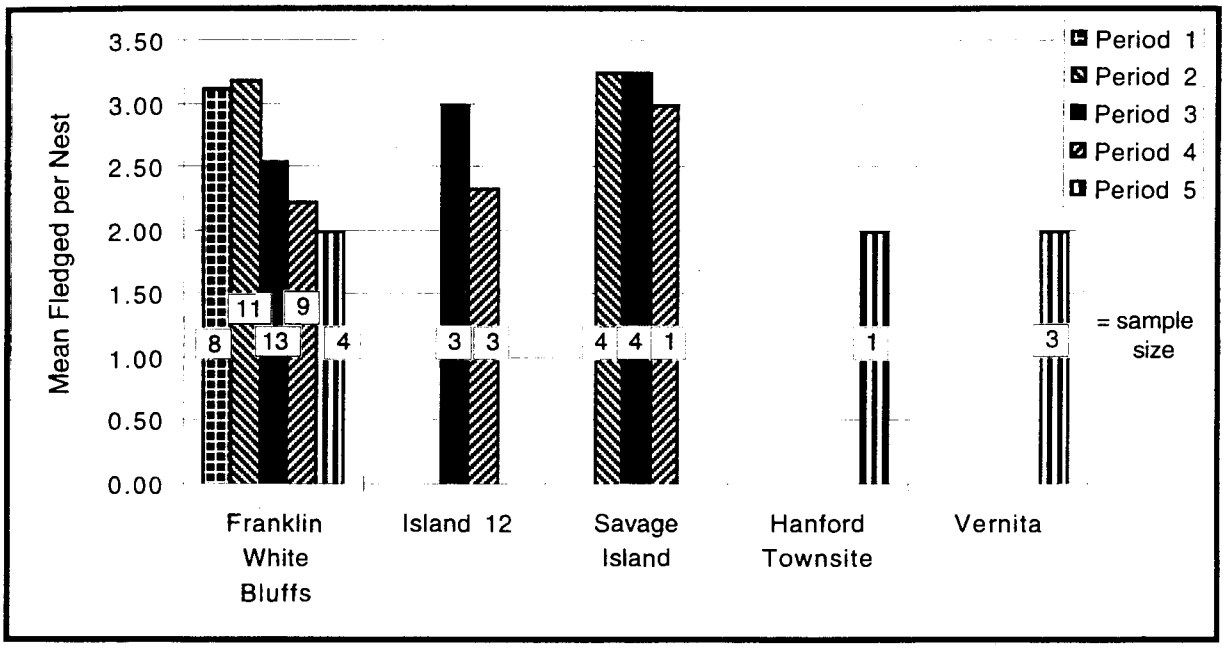

Figure 16. Fledging success of Great Blue Heron colonies in different incubation initiation periods along the Hanford Site, Washington, from 1995 through 1996.

relationship between proportion fledged per nest and brood size, indicating that higher mortality occurred in nests with larger broods (Fig. 11).

This agrees with Sullivan and Payne (1988) who noted that nests containing three or four nestlings, had the most aggressive interaction among siblings. They postulated that fewer cases of sibling rivalry occurred at nests containing less than three young due to less competition for food. It has been indicated that sibling rivalry may be the direct cause of death (Mock 1984; Mock and Parker 1986; Sullivan and Payne 1988). Although no direct mortality was attributed to sibling rivalry in this study, several indications suggest sibling rivalry occurs in Hanford Heron and could possibly cause direct mortality, including numerous aggressive interactions among nest mates and a chick with a open wound on its back. Further research would be required to determine the ultimate factor responsible for Great Blue Heron nestling mortality along the Hanford Site.

The observed difference in brood size and fledging success was most likely the result of clutch size variation. Even though I agree with most authors that higher fledging success is the result of larger clutches (Henny and Bethers 1971; Tomlinson 1975; Rodgers 1980; Tremblay and Ellison 1980; Pratt and Winkler 1985), it is also possible that clutch size was not the ultimate factor affecting fledging success. Another factor, such as renesting adults (Jenni 1969; Wolford and Boag 1971; Batt and Prince 1979; Butler 1995) or younger breeding birds (Lack 1968; Johnsgard 1973; Ryder 1980) could also result in smaller clutches.

Hatch Order

I found that individual fledging success among hatch order of nestling Great Blue Herons decreased from first to last hatched. Percent fledging success for first and second hatched was 93.9 percent and 90.6 percent respectively, whereas third

and fourth hatched was 80.0 percent and 64.3 percent respectively (Fig. 12). Several authors have indicated that a majority of Ardeid chick mortality is due to starvation of the smaller younger chicks which are unable to compete with older siblings for food (Pratt 1970; Collazo 1981; Quinney 1983; Mock 1985; David and Berrill 1987; Sullivan and Payne 1988). Although I frequently observed aggressive activities towards siblings during parental feedings, I didn't observe direct mortality due to these activities or attribute nestling mortality to starvation. However, the higher fledging success of the oldest and second oldest nestlings supports the findings of Mock (1985) and David and Berrill (1987) which indicated a dominance, size-related hierarchy exists in the nest.

Difference in hatch order fledging success agree with earlier studies suggesting decreased fledging success of younger siblings (Pratt 1970; Collazo 1981; Quinney 1983; Mock 1985; David and Berrill 1987; Sullivan and Payne 1988). These earlier studies attributed chick mortality to starvation, which resulted from food monopolization by older larger siblings. Although a size-related hierarchy was evident in the Hanford Herons and starvation of the younger siblings is probably the most likely cause of death, I cannot discount the possibility that falls from the nest (Butler 1995) or sibling rivalry may have been the direct cause of death (Mock 1984; Mock and Parker 1986; Sullivan and Payne 1988) in the observed difference.

Forage Distance

I found no relationship between distance to foraging areas and fledging success in the Hanford Herons. Although contrary to Simpson et al. (1987) who indicated that herons feeding near the colony had higher reproductive success, data collected in this study occurred during a record high river flow in 1996 and may not indicate normal foraging areas or distances. I believe reduced river foraging

success due to the high, fast, turbid water made further non-river areas, such as farm ponds and irrigation ditches, more appealing to foraging herons. I suspect that during normal flow years, Hanford Herons forage along the river shore more frequently and would likely provide a closer estimate of adult foraging distance than those observed in this study. Custer and Osborn (1978) and Bayer (1981) found tidal depth as a significant factor affecting foraging success and habitat selected by coastal nesting herons, while Benoit et al. (1993) showed water level only slightly affected foraging success in a riverine system. However, the difference in river flow rates between 1995 and 1996 (Fig. 17) are probably greater than those observed by Benoit et al. (1993).

I conclude that timing of incubation and brood size were the major factors that affected nest fledging success of Hanford Great Blue Herons. Adult herons that begin nesting earlier and raise more young to three weeks of age, have higher fledging success. However, it is highly probable that incubation initiation and brood size are related since brood size is most likely a function of clutch size, and clutch size has been indicated to decrease throughout the nesting season (Pratt and Winkler 1985; Butler 1995).

I also found hatch order was related to individual nestling Great Blue Heron fledging success. Older nestlings within a nest had a higher fledging success rate than younger siblings. Although I found no significant difference between nest fledging success and both nest eggshell thickness and forage distance, I believe that small sample sizes and high water levels limit these data respectively, and future studies would be needed to determine whether this is the case. Colony fledging success was not affected by colony size in this study.

Colony Eggshell Thickness

Most nesting adult herons forage close to their nest (Custer and Osborn 1978; Kushlan 1978; Thompson 1979; Marion 1989; Gibbs 1991; Benoit et al. 1993) and because colonial waterbirds are foraging on local food sources for several weeks prior to egg laying (Burger et al. 1993), eggshell thickness should represent an indication of individual colony health.

I found considerable variation in eggshell thickness within and between colonies. Health, differing diet due to territorial feeding, stress, contamination, and age are all possible reasons that may account for eggshell thickness variation among female Great Blue Herons. Herons foraging in close proximity to the colony, and thus having a similar diet or exposure to contaminants, is a possible reason for colony differences. It is also plausible that differing colony substructure, in which cast eggshells fall, may have allowed eggshells to be missed by observers due to thick vegetation, or rendered thin eggshell unusable for thickness measurements after landing on solid ground. Smaller colonies, yielding fewer eggshells, also increased the chance of collecting a greater proportion of eggs from one nest, consequently, biasing colony eggshell thickness.

In 1996, using eggshells from known nests, Tukey-Kramer multiple comparison test showed Savage (SAV) colony had significantly greater mean colony eggshell thickness than Franklin White Bluffs (FWB), Island 12 (POW), and Vernita (VER), with Hanford Townsite (HTS) not significantly different from any of the observed colonies. There are several possible reasons, including health, nutritional differences (Joyner 1994; Smith and Roudybush 1997) due to territorial feeding, stress affecting nutrition (Brue 1994), contamination, and age, that may explain the observed eggshell thickness differences among nests within a colony and among

colonies. I believe the close proximity of Savage (SAV) to the stable food sources provided along Savage Island Slough and at Ringold fish rearing facility (Fig. 15) resulted in healthier females laying eggs with thicker shells.

Analysis of all eggshells collected from VER, FWB, SAV, and POW in 1995 and 1996 indicated that mean colony eggshell thickness was marginally different between years at VER and POW. However, VER is a small colony and only two eggshells were collected in 1995, and since it is unknown which nests those eggshells came from, it is possible they were from the same nest and resulted in an over estimation of colony eggshell thickness. Also, repeated harassment from a Red-tailed Hawk nesting in the POW colony in 1996, including knocking an incubating bird off its nest, may have stressed the laying females, which I believe contributed to the observed difference in eggshell thickness between years at that colony. When I analyzed mean colony eggshell thickness from these four colonies during 1995 and 1996, SAV had a significantly greater mean colony eggshell thickness than VER, POW, and FWB.

It is important to note, that eggshell thickness as measured in this study were slightly thinner than those of other studies because shell membranes were absent when measurements were made. However, when mean membrane thickness was added to mean colony thickness for Hanford colonies, they overlapped colony eggshell thickness previously reported for the Hanford Reservation colony (Fitzner et al. 1988) and also British Columbia colonies (Elliott et al. 1989) (Table 13). I observed no broken eggshells during this study and mean colony eggshell thickness for all colonies was above the value associated with egg breakage (Anderson et al. 1969; Blus 1970; Coulter and Risebrough 1973).

Table 13. Eggshell thickness of eleven Great Blue Herons colonies and pre-1947 museum eggs.

Location	Date	Sample Size	Eggshell Thickness (mm) Mean	Range	Source
Pacific Northwest	Pre-1947	64	0.389	NL[a]	Anderson and Hickey (1972)
Hanford Reservation[b]	1981-1982	13	0.360	.32-.40	Fitzner et al. (1988)
Foundation Island[c]	1978	8	0.338	.34-.40	Fitzner et al. (1988)
Crofton[d]	1986	10	0.358	.312-.393	Elliott et al. (1989)
	1987	10	0.380	.359-.404	Elliott et al. (1989)
UBC[d]	1986	7	0.357	.307-.408	Elliott et al. (1989)
	1987	27	0.364	.316-.420	Elliott et al. (1989)
Sidney[d]	1986	4	0.384	.370-.396	Elliott et al. (1989)
Nicomekl[d]	1986	5	0.353	.328-.380	Elliott et al. (1989)
Vernita[e]	1995	2	0.408	.403-.413	This Study
	1996	9	0.365	.333-.413	This Study
Franklin White Bluffs[e]	1995	23	0.356	.278-.415	This Study
	1996	68	0.361	.313-.424	This Study
Savage Island[e]	1995	2	0.410	.368-.452	This Study
	1996	12	0.399	.360-.429	This Study
Island 12[e]	1995	9	0.375	.356-.395	This Study
	1996	18	0.360	.318-.408	This Study
Hanford Townsite[e]	1996	3	0.367	.354-.380	This Study

[a] NL = not listed
[b] Hanford Reservation data from Benton White Bluffs Colony.
[c] Located in Washington along the Columbia River, downriver from Hanford.
[d] Colonies located in British Columbia.
[e] Mean membrane thickness of .062 mm was added to the mean and range eggshell thickness.

I conclude that, even though mean eggshell thickness differences exist among Hanford Great Blue Heron colonies, all mean colony thickness values are larger than values known to affect reproduction. Nonetheless, further research would be required to identify the reasons for the observed eggshell thickness difference among Hanford heron colonies.

I believe the minimal interannual variation at sites, using cast eggshells, will provide a reliable, inexpensive, nonlethal, and unobtrusive way for continued monitoring of Hanford heron colonies. However, if cast eggshells are to be continually collected, I recommend that eggshells be measured with and without shell membranes whenever possible. Eggshell thickness measurements without membranes will allow comparisons to be made with the results presented in this study, while measurements with membranes will allow direct comparisons to be made with other studies, as well as providing a better estimate of mean membrane thickness than results presented here.

Reproduction

The 2.36 young fledged per active nest I observed, is higher than the 1.91 needed to maintain a stable population (Henny 1972). This suggests that the Hanford Great Blue Heron population is capable of increasing, however, the nesting population has decreased 43% since 1984, even though the number of active colonies along the Hanford Reach has increased (Table 14). Low survival of fledglings to breeding age, low adult immigration rates, destruction of colony trees, and shooting by humans are all possible explanations for the decrease in nesting adults. Heron excrement eventually kills colony trees (Julin 1986), which might become a problem in an area with a narrow riparian zone and few suitable colony

Table 14. Summary of Great Blue Heron reproductive success along the Columbia River, adjacent to the Hanford Site, Washington.

Year	No. of active colonies	Nesting pairs	No. fledged per active nest	Source
1978	1	40	NA[a]	Rickard et al. 1978
1981	1	84	1.76	Blus et al. 1985
1984	1	100	NA[a]	Blus et al. 1985
1995	8	69	NA[a]	This study
1996	6	57	2.36	This study

[a] NA = not available

trees, such as the area located along the Hanford Site. However, use of powerline towers by two colonies in this study area, including one study colony utilizing a 240 kv powerline tower, agrees with earlier studies indicating use of man-made structures as suitable habitat for nesting Great Blue Herons (Henny and Kurtz 1978). Also, to my knowledge, shooting of Great Blue Herons did not occur along the Hanford Site during this study. However, legal shooting of herons in 1997 by Animal Damage Control (ADC) at Ringold hatchery indicates that shooting of herons persists, and similar incidents prior to this study may have contributed to the observed decline. It is also possible that this is normal variation in the Hanford population. The increase in the number of active colonies along the Hanford reach could also be due to heron excrement (Julin 1986), which may have killed the nest trees of the historical colony site. Nonetheless, continued research would be required to determine the reason for the observed decrease in nesting adults and increase in active colonies.

GENERAL CONCLUSION

SUMMARY

My literature review, showed that a wide variety of factors affect productivity in colonial waterbirds. I found incubation initiation, brood size, and hatch order were all factors affecting Great Blue Heron fledging success along the Hanford Site. Fledging success remained unaffected by year, nest eggshell thickness, colony size, and forage distance in this study. The factors I found to affect Great Blue Heron productivity will aid future studies in determining the overall factors affecting their reproductive success.

My results indicate mean eggshell thickness differences among Great Blue Heron colonies along the Hanford Site. Mean colony eggshell thickness values were above those known to cause reproductive impairment and egg sampling for contaminants is not warranted at this time. However, if Great Blue Heron eggs are to be chemically analyzed for contaminants, I recommend selecting those colonies with eggshell thickness values on the low range to allow for the highest probablity of detecting contaminants. My results also showed small interannual variation in mean colony eggshell thickness, using cast eggshells. This suggests that eggshell thickness remained fairly consistant between years at a colony and should provide an inexpensive way to continue monitoring heron colonies with the passage of time.

In this study, I found fledging success per active heron nest to be considerably higher than the value needed to maintain a stable population. This implies the Hanford heron population is reproductively healthy and should be increasing or at least maintaining. However, evidence suggests the Hanford heron breeding population has been declining, and it is unclear why this is occuring. High mortality of first year herons (Butler 1995) and shooting of adults at Ringold fish

hatchery are probable contributing factors. Further research is required to determine the reason for the decline in breeding herons along the Hanford Site.

I also found no difference in fledging success between marked and unmarked nests, as well as minimal mortality in post mobile stage nestlings. This information indicates that future Hanford heron reproductive studies can estimate fledging success using unmarked nestlings and post mobile stage mortality reported here.

I conclude the fledging success and eggshell thickness of Hanford Great Blue Herons is representative of a healthy population. However, future investigators might want to examine the reason for the observed difference in eggshell thickness among colonies. I suggest that if egg sampling occurs, it can be done without affecting fledging success. Since I observed the youngest sibling in a nest to have the lowest fledging success rate and no nests fledged more than four young, sampling the last egg laid (determined from specific gravity) (Custer et al. 1992) from nests with clutches of five or more eggs should not adversely affect heron reproductive success.

Furthermore, it appears that colony foraging areas are separate from one another along the Hanford Reach, except for adults foraging at the fish rearing facility (Fig. 13). This agrees with previous studies indicating herons forage in close proximity to the colony (Custer and Osborn 1978; Kushlan 1978; Thompson 1979; Marion 1989; Gibbs 1991; Benoit et al. 1993) and suggests that Hanford heron colonies could be used to monitor different stretches of the Hanford Reach. Because of the high rate of productivity in Hanford herons, I believe that some contaminant sampling, using nestlings herons, can be done without adversly affecting their productivity. Nestlings sampled prior to fledging would provide an indication of local contamination in the aquatic food chain.

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Appendix A. Description of equipment used on Great Blue Heron study, along the Hanford Site, Richland, Washington from 1995 through 1996.

Equipment	Company or Description
8 mm camcorder	Thomson Consumer Electronics Inc., Indianapolis, Indiana, USA
Extending pole	Mr. Longarm, Greenwood, Missouri, USA
62 foot aerial platform	Ivy Hi-lift, Pasco, Washington, USA
48 foot aerial platform	Seco Construction Equipment inc., Dennewick, Washington, USA
Transmitters	Advanced Telemetry Systems, Isanti, Minnesota, USA
Tag and transmitter attachment	Allflex, Dallas, Texas, USA
Boat	16 foot Hewscraft equipped with a 50 horsepower outboard motor
Leg-hold trap	# 3 padded leg-hold trap using 1.5 soft catch springs (see King et al. 1994)